



YINGJUN PAN

ANALYSIS AND EXPERIMENT OF A VTOL FLAPPING WING
ROTOR MICRO AIRCRAFT

SCHOOL OF AEROSPACE TRANSPORT AND MANUFACTURING

PhD

Academic Year: 2020 - 2023

Supervisor: Shijun Guo

Associate Supervisor: James Whidborne

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ABSTRACT

This thesis presents an in-depth study of the aerodynamic and structural analysis of a novel bio-inspired flapping wing rotor (FWR) micro aerial vehicle (MAV) capable of vertical take-off and landing. The FWR is characterized by a combination of active flapping motion with passive rotation of the wings in an asymmetric installation to produce a significantly higher lift coefficient than traditional flapping wings. This research is aimed at further enhancing the FWR MAV's efficiency and aerodynamic performance with flight capability and stability. This is approached by improving the FWR kinematics of motion and mechanism through analytical, numerical simulation, and experimental methods.

In the first step, an efficient wing rotation method that allowed a small angle of attack in the downstroke and a larger one in the upstroke was considered. A novel Passive Pitching Angle Variation (PPAV) device, replacing traditional active rotation, was developed and integrated into the flapping mechanism. Using a high-speed camera and a load cell device for experiments, the PPAV-integrated FWR demonstrated a significant increase in aerodynamic efficiency compared to its constant pitch angle counterpart.

In the second step, the study focused on enhancing FWR-MAV power efficiency by integrating springs into the mechanism, thereby reducing input power due to the counterbalance between elastic and inertia forces. Numerical analysis and experimentation with an FWR test model were conducted to simulate and measure the resultant kinematics of motion and forces. Specific emphasis was placed on the influence of spring stiffness on the FWR's aerodynamic and power efficiency. This led to the development of a PPAV-integrated FWR model capable of remote-controlled vertical take-off and hovering.

In the third step, the study explored wing flexibility's impact on FWR's unsteady aerodynamics using Fluid-Structure Interaction (FSI) analysis and experiments. A novel dragonfly-like wing with a curved sweep-back wingtip demonstrated aerodynamic benefits. The study elucidates the mechanism of wing bending deformation linked to vortex variation, implying that optimal spanwise variable

stiffness can enhance lift and power efficiency. Employing flexible wings, the FWR model's lift significantly increased from 25 g to 51 g, highlighting enhanced efficiency and payload capacity.

The study finally explored the FWR-MAV's flight performance and efficiency, including VTOL and forward flight. It proposed a transformable MAV concept from VTOL FWR mode to a bird-like flapping-wing mode in forward flight. A test model was built to validate the transformation concept. Using MSC.ADAMS/Simulink co-simulations and a quasi-steady aerodynamic method, the flights of the FWR model in both flight modes were simulated and stability was demonstrated.

Keywords:

Flapping Wing Rotor, Passive Pitching Angle Variation, Elastic Mechanism, Aerodynamic Performance, Power Efficiency, Flight Simulation

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LIST OF ABBREVIATIONS

MAVs	Micro Aerial Vehicles
UAV	Unmanned Aerial Vehicle
ISR	Aerial Intelligence, Surveillance, And Reconnaissance
VTOL	Vertical Take-Off and Landing
STOL	Short Take-Off and Landing
FWR	Flapping-Wing Rotor
FW	Flapping Wing
AoA	Angle of Attack
LE	Leading Edge
LEV	Leading Edge Vortex
TEV	Trailing Edge Vortex
AR	Aspect Ratio
QS	Quasi-Steady

LIST OF COMMONLY USED SYMBOLS

Re	Reynolds Number
μ	Dynamic viscosity (N·s/m ²)
c	Wing Chord Length (m)
ω	Flapping Angular Velocity (rad/s)
U_{ref}	Reference Velocity
U_r	Relative Flow Velocity (m/s)
U_f	Flapping Velocity (m/s)
U	Forward Velocity (m/s)
w_i	Downwash Velocity (m/s)
ψ	Rotation Angle (rad)
ϕ	Flapping Angle (rad)
α	Pitching Angle (rad)
$\dot{\psi}$	Rotation Speed (rad/s)
$\dot{\phi}$	Flapping Velocity (rad/s)
$\dot{\alpha}$	Pitching Velocity (rad/s)
f	Flapping Frequency (Hz)
Φ	Flapping Amplitude (rad)
$\hat{t}$	Nondimensional Time
t	Real Time (s)
$\hat{t}_r$	Nondimensional time when reverse starts.
α_e	Effective Angle of Attack (rad)
α_u	Geometric Angle of Attack of Wing at Mid-Upstroke (rad)
α_d	Geometric Angle of Attack of Wing at Mid-Downstroke (rad)
α_0	Mean Angle of Attack (rad)
$\Delta\alpha$	Pitching Amplitude (rad)
C_L	Lift Coefficient
C_M	Rotational Moment Coefficient
$\bar{C}_L$	Mean Lift Coefficient
$\bar{C}_M$	Mean Rotational Moment Coefficient
$\bar{C}_P$	Mean Power Coefficient

C_H	Quasi-Steady Aerodynamic Coefficients Due to Wing Translation (Empirical)
C_V	Quasi-Steady Aerodynamic Coefficients Due to Wing Translation (Empirical)
C_{rot}	Quasi-Steady Aerodynamic Coefficients Due to Wing Pitching (Empirical)
ρ	Air Density (kg/m ³)
S	Wing Area (m ²)
$\bar{c}$	Mean Chord Length (m)
η	Non-Dimensional Rotation Speed
P_f	Power Factor
St	Strouhal Number
a	Length of the Flapping Bar (m)
r	Crank Arm Length (m)
l	Connecting Rod Length (m)
λ	Ratio of Crank Arm Length to Connecting Rod Length

Chapter 1 Introduction

1.1 Research Background

Micro aerial vehicles (MAVs), which are ideally adapted for executing aerial intelligence, surveillance, and reconnaissance (ISR) inside buildings and confined spaces, have attracted significant interest from both military and civilian end users in the past decades (Hassanalian & Abdelkefi, 2017; Petricca, et al., 2011). They can be categorized into three primary classifications: fixed-wing, rotary-wing, and flapping-wing. While a fixed-wing MAV excels in aerodynamic efficiency and cruising endurance, it lacks vertical take-off and landing (VTOL) and hovering capabilities. Furthermore, its efficiency markedly diminishes at extremely low Reynolds numbers. Although a rotary-wing MAV offers VTOL capability, the aerodynamic performance also deteriorates significantly at a very low Reynolds number. Moreover, the rotary wing is not counted in the category of biomimetic MAV. Therefore, flapping wings inspired by natural flyers serve as an alternative solution to dealing with MAV challenges in very low Reynolds number scenarios, which many scientists and robotic engineers have recently been fascinated to develop.

Flapping wings utilize unsteady aerodynamic mechanisms for effective lift generation at low Reynolds numbers, thus presenting suitability for miniaturization (Ellington, 1999). An insect-like flapping wing (FW) MAV can produce lift in hover more efficiently with less power compared to such a similar size rotary-wing (Hawkes & Lentink, 2016; Zheng et al., 2013). FW-MAVs also have a lower power demand in level flight compared to a fixed-wing MAV that often adapts a vertical propulsion system (Sachs, 2016). The development of an FW-MAV capable of VTOL and hovering has been motivated by scientific founding, and commercial and military applications in the past few years. The hummingbird-like aerial vehicle developed by Defence Advanced Research Project Agency (DARPA) in 2011 shows an encouraging example . The biomimetic FW-MAVs could also be used to guide insect pollination or artificial pollination to boost crop yield (Chechetka *et al.*, 2017).

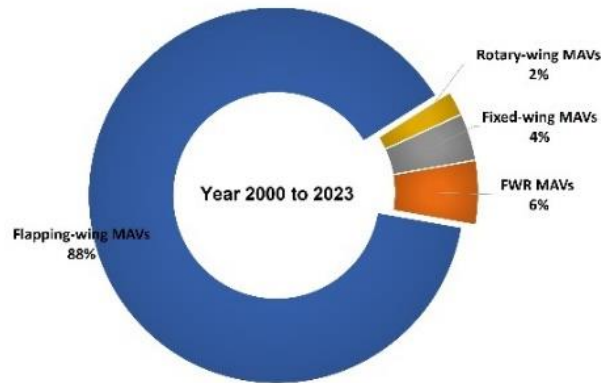
Engineering insect-inspired FW-MAVs are particularly challenging due to the differing principles of attitude control and stability compared to bird-like FW-MAVs. Bird-like FW-MAVs utilize their tails for attitude control, whereas insect-like FW-MAVs delicately modulate wing kinematics, including stroke amplitude, flapping speed, angle of attack, and stroke-plane deviation. Most insect-like FW-MAVs are tailless and rely on flapping motion to produce control forces, resulting in agile maneuvers with more degrees of freedom (Bomphrey & Godoy-Diana, 2018; Nachtigall, 2018). The progression of insect-inspired FW-MAVs proficient in agile maneuvers and hovering in both indoor and outdoor spaces is a promising avenue for future applications.

Aiming to enhance aerodynamic efficiency in FW-MAV design, an innovative flapping-wing rotor (FWR), amalgamating traits from bio-inspired flapping wing and rotary wing, has been developed. This compound biological configuration harnesses the advantages of multiple kinematics of flapping and rotation motions and is capable of VTOL and hovering. In 2003, Vandenberghe et al. (2004) observed from their experiments that vertical flapping motion of wings generated thrust and imparted horizontal rotation to the wings. In 2007, Fitchett (2007) at the University of Maryland constructed a metal torqueless flapping rotor for MAVs, named 'Flotor', capable of producing lift and thrust akin to those produced by flying animals. This mechanism featured actively flapping wings driven by a motor and rotating passively. However, prior to Guo et al.'s proposal of the FWR concept (2009), the emphasis of these studies was on the physical phenomenon of flapping blades generating thrust, with minimal attention given to the contribution of wing flapping and rotation to lift enhancement for FW-MAVs.

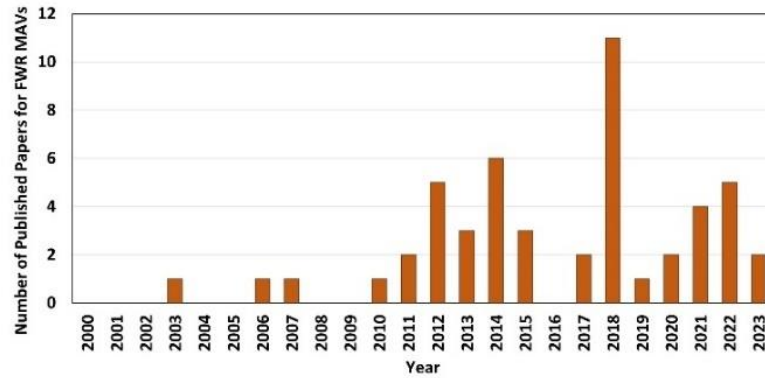
Guo et al. (2009) substantiated the practicality of the FWR concept of the FWR concept using a 9-g prototype with compliant joints, driven by a piezoelectric actuator. Their experiments showcased the potential for power efficiency by utilizing system resonance and aeroelastic effects. In 2012, Guo and Li (2012) made further experimental and numerical studies based on an enlarged piezoelectric actuated FWR. This study furnished valuable experimental data to corroborate theoretical and numerical models, thereby offering an effective

approach for designing FWRs, particularly in the computation of unsteady aerodynamic forces.

Piezoelectric actuators have high frequency and power density but inherently small amplitude, requiring a mechanical amplifier to achieve the necessary large amplitude for flapping wings. On the other hand, the high voltage power required by piezoelectric actuators is a practical barrier to their use in MAVs. Currently, a micro-DC motor is the most practical option for FWR-MAV development. In 2011 and 2012, Li et al. (2011) and Wu et al. (2012) developed a 9.1-g and an 8.4-g FWR model, respectively, driven by an electric motor and simple crank-slider mechanism for lift measurement and FWR-MAV feasibility evaluation. Guo et al. (2018) manufactured and tested a flyable 2.6-g FWR model and achieved the first vertical take-off flight without control in 2014, which is the lightest flyable FWR model so far. Dong et al. (2020) built a 34-g FWR-MAV and achieved free flight, making it the first flying FWR model with an onboard power and control system.



(a)



(b)

Figure 1-1 (a) Publications on MAVs during the period from 2000 to 2023 (Data were sourced from the Scopus database employing the search keyword: TITLE (flapping-wing and robot or vehicle or MAV) for flapping-wing MAVs , TITLE (fixed-wing MAV) for fixed-wing MAVs, TITLE (rotary-wing or rotorcraft and MAV) for rotary-wing MAVs, TITLE (flapping-wing rotor), TITLE (flapping-rotary wing) and TITLE (flapping perturbed revolving wing) for FWR-MAVs; (b) Number of papers published on FWR-MAVs each year.

In the previous decade, a limited group of researchers have dedicated their efforts to investigating FWR technology, comprising around 6% of publications in core journals within the MAV field as depicted in Figure 1-1. The research on FWR has advanced through theoretical and experimental studies, which highlights the FWR's unique wing kinematics of motion and aerodynamic superiority over the traditional insect-like FWs and rotary wings.

The advancement of current bio-inspired FW-MAVs and FWR-MAVs is impeded by ongoing challenges, especially limited endurance due to lift generation and power efficiency in complex environments. Enhancing the aerodynamic efficiency of FWR-MAVs can be achieved through optimizing wing kinematics, geometric features, and flexible structures. Furthermore, drawing inspiration from insects that utilize elastic storage in their flight muscles, thorax, and wing hinges to conserve energy, mechanical FWRs can employ elastic actuators to reduce power consumption. This enables longer flight durations, even with constrained onboard energy resources, due to efficient propulsion and energy utilization.

Another major challenge for current FWR-MAVs is the absence of a well-designed control mechanism tailored to the unique combination of insect-like flapping wings and rotary wings, as well as an onboard control board for attitude and altitude regulation. This discrepancy results in a significant gap between the flight capabilities of existing FWR-MAVs and the more well-developed FW-MAVs that can perform freely controlled flight and agile manoeuvres. Consequently, it is essential to conduct research that furthers the development of FWR-MAVs by enhancing aerodynamic performance, power efficiency, and control capabilities.

1.2 Research Aim and Objectives

This Ph.D. research aims to conduct an in-depth aerodynamic and structural analysis of a bio-inspired, flapping-wing micro aircraft with VTOL capabilities.

The objectives are outlined as follows:

1. To address the challenges faced by current FWR-MAVs by exploring a method for enhancing lift generation and developing an innovative FWR mechanism with optimal motion kinematics (linked to Chapter 3).
2. To create an efficient mechanism system that improves the power efficiency of FWR-MAVs (linked to Chapter 4).
3. To investigate the unsteady aerodynamic mechanism in natural flight and optimize wing structures for FWR-MAVs, with the aim of improving aerodynamic performance and efficiency (linked to Chapter 5).
4. To establish a control strategy for the optimized mechanical FWR model to fulfil VTOL capabilities and sustained flight (linked to Chapter 6).

1.3 Contributions

This thesis presents a systematic study on bio-inspired FWR-MAVs, highlighting the progress of FWR-MAVs from laboratory research to flight control toward potential applications. The primary contributions of this research are as follows:

1. Designed novel bio-inspired FWR-MAVs with passive pitching angle variation for high lift production, achieving take-off and hovering flight using an onboard power source and remote-control system.

2. Identified crucial parameters for optimizing the FWR mechanism and proposed an efficient elastic mechanism for incorporation into the mechanical system, improving the power efficiency of the FWR model.
3. Advanced the understanding of FWR wing's dynamic deformation, unsteady aerodynamic mechanisms, and the effect of wing flexibility on aerodynamic performance, enabling the biomimetic wing design of FWR-MAVs with improved lift augmentation and power efficiency.
4. Developed a control strategy for the current FWR-MAV model, representing the first investigation of take-off and forward flight mode transition for future practical applications.

1.4 Thesis Structure

This thesis adopts a paper-format style, as an alternative to the monograph format, in accordance with the Guidance Document: Format Options for PhD Thesis Formats v1.3 Jan 2017. Chapters 1 and 2 provide the introduction and literature review, respectively. Chapters 3 through 6 serve as the primary technical chapters, presenting the core outcomes of the Ph.D. research. Each of these technical chapters is presented as a distinct work package, encompassing an introduction, methodology, results, and discussion.

Specifically, the thesis is structured as follows:

Chapter 2 begins with a comprehensive introduction to flapping wing aircraft and offers a research review on the recent progress in FWR-MAV development. It analyses key advances, challenges, and future research directions in the field. Chapter 2 also motivates the aim and demonstrates the need to conduct an in-depth aerodynamic and structural analysis of the FWR aircraft.

Chapter 3 discusses the aerodynamic performance of FWR-MAVs featuring passive pitching angle variation. Two types of FWR models (FWR Model.1 and FWR Model.2 as shown in Figure 1-2) with passive pitching angle variation are presented through design and experimentation. The influence of passive pitching angle on enhancing the aerodynamic performance of FWRs for enabling flight is examined.

Chapter 4 details the investigation of an efficient elastic mechanism for a flyable FWR-MAV, utilizing dynamic numerical analysis. The model (referred to FWR Model.3 and shown in Figure 1-2) was validated through experimental measurements and flight tests. When compared to the baseline springless model, the elastic mechanical system demonstrated increased lift production and reduced power consumption.

Chapter 5 conducts an extensive analysis of the effect of dragonfly-like wing shape and flexibility on the aerodynamic performance of FWR-MAVs using unsteady aerodynamic coupling simulations through computational fluid dynamics (CFD) and computational solid dynamics (CSD) methods, based on the FWR Model.2 depicted in Figure 1-2. This fluid-structure interaction (FSI) problem centres on examining the influence of wing elastic deformations, including twist and bend, on FWR aerodynamic performance. The effectiveness of this dragonfly-like flexible wing is validated by experiments and flights.

Chapter 6 introduces a flight control mechanism for an FWR-MAV, which is refined based on FWR Model.3 as shown in Figure 1-2. This mechanism encompasses a flight mode transition mechanism, stabilizers, and control surfaces. The design emphasizes a flight mode transition from VTOL using an FWR layout to forward flight with an FW layout.

Chapter 7 presents a conclusion of research work, remarks on each objective, and suggests future work in the field.

In short, Figure 1-2 presents the FWR models developed in this thesis and illustrates the relationships and corresponding models from Chapter 3 to Chapter 6.

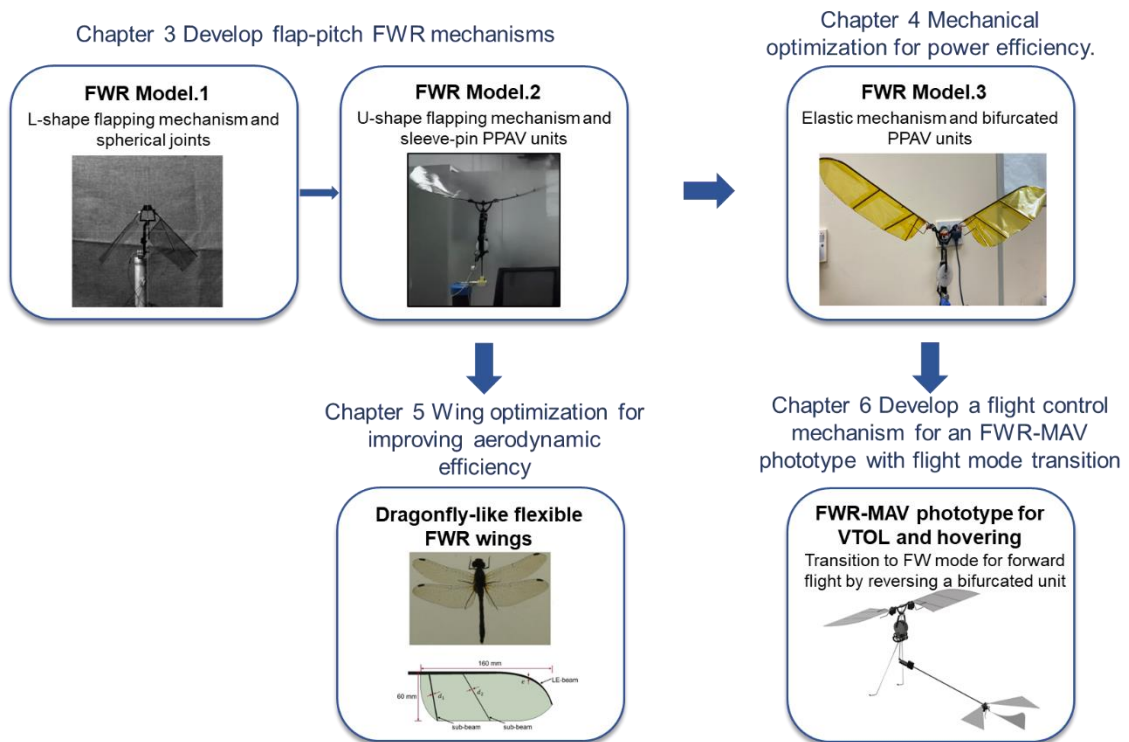


Figure 1-2 Diagram illustrating the thesis structure with an outline of FWR Model

Chapter 2 LITERATURE REVIEW

2.1 Flapping Wing Aircraft

After achieving powered flight in aviation history, humans have developed various aerial vehicles. After the nineteenth century, people paid attention to gliders and then the internal combustion engines dramatically fostered the development of fixed-wing aircraft. Nowadays, major innovations in aircraft configuration design are increasingly challenging. Helicopters, inspired by dragonflies, can fly in multiple directions (Usherwood & Lehmann, 2008). Aircraft designers track early stages of flight exploration inspired by nature in search of advances. Concurrently, advanced computational tools and mature engineering software enable refined and specialized aircraft design. As a result, numerous aerial vehicles tailored for specific environments have emerged.

Early flying machines imitated the flapping wings of birds using feathers or artificial materials. Over time, wings transitioned from being manually flapped to mechanism driven. Flapping wing aircraft (FWA) generate lift and thrust through active reciprocating wing motions (Chen et al., 2010). Compared with traditional fixed-wing aircraft, flapping wing aircraft offer better maneuverability and power efficiency in low-speed flight (Sun et al., 2017). Additionally, flapping wings usually have lower tip speeds than propellers, resulting in quieter operation and reduced damage potential when encountering people or property (Breuer, 2019). Bird-like flapping wing aircraft can achieve short take-off and landing (STOL), while insect-inspired vehicles may perform vertical take-off and landing (VTOL).

2.1.1 Categories of Flapping Wing Aircraft

Flapping wing aircraft span from large-scale ornithopters to micro air vehicles (MAVs). They are typically classified as manned engine-powered or human-powered ornithopters, and unmanned flapping wing vehicles resembling birds or insects.

Large-scale manned ornithopters have been developed by global institutions for trials. Its challenges include immature unsteady aerodynamics, structural design, materials, and flapping control. In 2006, A team at the University of Toronto

Institute for Aerospace Studies (UTIAS) achieved a 14-s engine-powered ornithopter flight, but further development was hindered by structural issues (Hein, 2006). In 2010, UTIAS built a human-powered ornithopter, Snowbird, which flew for 19.3 s, covering 145 m at 25.6 km/h ('Successful Flight of the Snowbird', 2010). The trial highlighted areas for improvement, such as weight reduction and increased propulsive efficiency through better wing kinematics.

Unmanned flapping wing vehicles imitating birds, bats, or insects, are characterized by their small size, lightweight, agility, and compact power and control systems. They are relatively simple in design and construction, appearing in many models for study, industrial, and military applications, as well as commercial toy products ranging from rubber-band-powered prototypes to radio-controlled models. They generate interest due to their long flight times, low weight, and resemblance to real flying animals.

2.1.2 Applications of Flapping Wing Vehicles

Flapping wing vehicles, also known as flapping wing robots, serve various research and practical applications, including bioscience development, wildlife monitoring, and conservation efforts. Biologists use these robots to study flight evolution and the mechanical basis of natural selection (Breuer, 2019). Biomimetic flapping wing vehicles closely imitate a bird or insect, allowing them to be assimilated into a bird flock and even attracting real birds to play with them or be chased by their natural enemies. Colorado Parks and Wildlife utilized a hawk-like ornithopter to help conserve the endangered Gunnison sage grouse. The artificial hawk, controlled by an operator, encourages grouses to stay on the ground, facilitating their capture for study.

Bio-inspired flapping wing vehicles, with their agility, maneuverability and capability of flying indoor and outdoor, have garnered interest for various military applications. They are well-suited for aerial Intelligence, Surveillance, and Reconnaissance missions, as their stealth capabilities allow them to operate in complex environments without detection. Companies like AeroVironment and Animal Dynamics have developed flapping wing MAVs for such purposes (Dempsey, 2020). Moreover, flapping wing aircraft can navigate narrow urban

spaces to support cooperative combat for unmanned aerial vehicle (UAV) swarms, minimizing harm to civilians (Hou & Liu, 2020). They can also carry electronic jammers to disrupt enemy communication systems, capture important information, and serve as communication relay platforms during failures. Additionally, these vehicles can access hazardous areas, such as biological or nuclear accident sites and natural disaster zones, providing valuable video surveillance, terrain survey, and delivery capabilities.

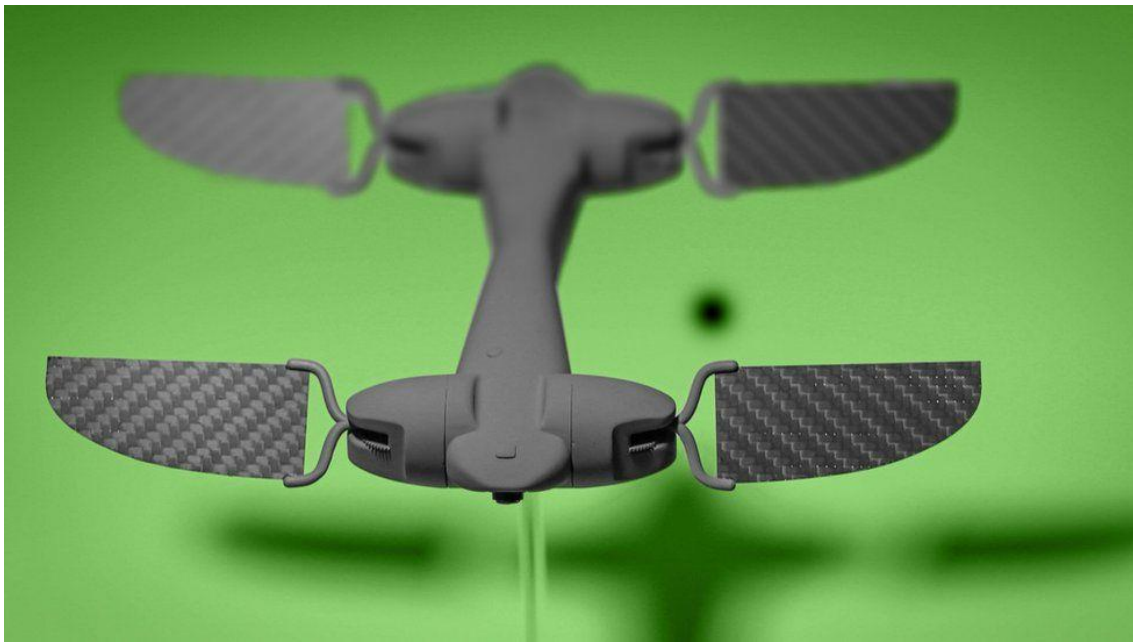


Figure 2-1 The Skeeter Drone Developed by the Animal Dynamics, Inc (Dempsey, 2020).

In civilian applications, flapping wing vehicles can assist in building inspections for rescue missions, monitor criminal activities, and patrol borders for law enforcement agencies. They can aid in agricultural tasks, such as guiding insect pollination, artificial pollination, and pest control in greenhouses to boost crop yield (Chechetka *et al.*, 2017). Airports, like Amsterdam Airport Schiphol, have radio-controlled robot birds to scare away birds that could damage the engines of airplanes. Companies like Drone Bird and Festo have developed advanced drone birds for various industries, including waste management, as well as autonomous navigation systems for future networked factories. These artificial birds can

optimize internal factory spaces by transporting materials and goods and addressing production bottlenecks.

In summary, there are primarily four application domains for flapping wing vehicles: unobtrusive surveillance in security, bird/pest control in natural environments, airports, or agriculture, monitoring and navigation systems in industry, and specialized uses in movies or performances.

2.1.3 Challenges of Flapping Wing Vehicles

2.1.3.1 Configurations of MAVs

In the past decade, micro air vehicles (MAVs) have emerged as a new class of UAVs, typically featuring dimensions no greater than 15 cm and gross takeoff weights of around 100 g or less (Pines & Bohorquez, 2006). Given their diminutive size and low flight speed, MAVs usually function within sensitive Reynolds-number regimes of 10^5 or lower (Shyy *et al.*, 2011). Existing MAV configurations can be categorized into fixed wing, rotary wing, and bio-inspired flapping wing types.

Fixed wing MAVs are small airplane with fixed lifting surfaces and control surfaces. Their design is relatively straightforward, and they are typically powered by propellers and have relatively fast forward flight speed, thus taking a competitive edge on long endurance outdoor missions. However, they cannot hover. Rotary wing MAVs, resembling micro-scale helicopters, provide VTOL and hovering capabilities. However, the proportionate mass of the propulsion system, encompassing batteries, motor, and transmission, typically accounts for over 60% of the total mass of the vehicle. Moreover, helicopter configurations often require an extra rotor to counteract reverse torque. Consequently, rotary wing MAVs face challenges like increased system complexity, higher power requirements, and limited loiter times. For example, the hovering performance of Micro Coaxial Rotorcraft is less efficient than conventional full-scale rotorcrafts, requiring more power to stay aloft (Bohorquez & Pines, 2004).

Bird-like and insect-like flapping wings represent two distinct subclasses of flapping wing MAV (FW-MAV) design. Bird-like flapping wing vehicles generate

lift by flapping motion with synchronized and small Angle of Attack (AoA) variations and require an initial airspeed before taking off, similar to fixed-wing configurations. Consequently, these vehicles cannot hover (Galiński & Zbikowski, 2007). In contrast, insect-like flapping wing vehicles, mimicking insect flight kinematics, exhibit large flapping amplitudes and rapid AoA variations between upstrokes and downstrokes, enabling hovering and VTOL capabilities. Insect flight maneuvers, including backward take-offs, sideways flights, and inverted landings, attract substantial interest from MAV researchers. In summary, the versatile mobility of Flapping-Wing Micro Air Vehicles (FW-MAVs), encompassing capabilities such as forward flapping flight, hovering, gliding, and even terrestrial and aquatic locomotion, provides a significant edge over other types of Micro Air Vehicles.

2.1.3.2 Aerodynamics at Low Reynolds Number

FW-MAVs operate at low flight speeds and face unfavorable aerodynamic characteristics compared to larger, manned vehicles due to low Reynolds numbers. The Reynolds number Re is a dimensionless value that characterizes the flow over a body submerged in a fluid. It is given by the equation:

$$Re = \frac{\rho V c}{\mu} \quad (2-1)$$

In this expression, ρ denotes the density of the air, V represents the velocity of the airflow, c is the characteristic chord length of the aerofoil, and μ stands for the dynamic viscosity of the fluid. At a low Re , the flow around an aerofoil, initially laminar, is prone to separation in response to even slight adverse pressure gradients. As Re decreases, the increased effect of viscous dissipation tends to delay the transition to turbulent flow or hinder the reattachment of the flow, thereby affecting aerodynamic performance adversely (Shyy *et al.*, 2011). This phenomenon is depicted in Figure 2-2, where it is shown that in the Re regime of 10^5 or lower, the lift-to-drag ratio (defined as aerodynamic efficiency) of smooth airfoils drops considerably due to the flow separation (Petricca *et al.*, 2011).

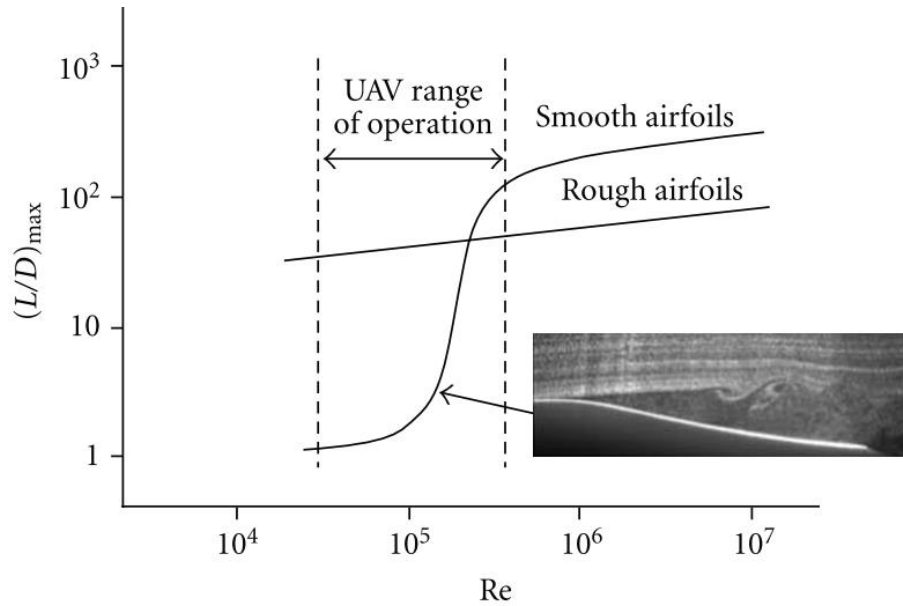


Figure 2-2 Lift-to-drag ratio variation with Reynolds number (Petricca et al., 2011)

Although recent advances in understanding the fundamental aerodynamic mechanism of flapping wings, including delayed stall, wake capture, rotational circulation and bound circulation, have provided researchers with a framework of low-Reynolds-number flight (Weis Fogh, 1973; Spedding & Maxworthy, 1986; Dickinson et al., 1999; Sane & Dickinson, 2001; Liu et al., 1998), researchers have yet to establish a direct correlation between the operational mechanisms and the resultant forces generated during flight. Therefore, existing flapping wing vehicles do not parallel the aerodynamic performance of small birds and insects with respect to stability, maneuverability, and efficiency within the Reynolds number range of $50 < Re < 3 \times 10^4$. Developing new analytic methods and computational tools to study complex unsteady aerodynamic flow behavior at low Reynolds numbers for bio-inspired FW-MAVs is essential.

2.1.3.3 Geometric Wing Scaling and Adaptive Wing Design

Bionic flapping wing aircraft face challenges of structural miniaturization due to the mass fraction associated with lightweight, flexible, and adaptive wing structures. The structural design parameters of FW-MAVs include wingspan, aspect ratio and wing loading. Rayner concluded a number of geometric 'scaling law' of birds referred to a function of total body mass (Rayner, 1979; Rayner, 1988). In contrast to birds with equivalent geometric dimensions and weight, the

higher wing loading for FW-MAVs results in the need for faster flight to obtain enough lift and consume additional power to counteract induced aerodynamic drag, leading to decreased efficiency, agility, and maneuverability.

Natural flyers perform morphological shape changes in wing geometry and stiffness during flight, expanding their flight envelope. The morphing capability that modifies lift and drag, a notable merit in bionic flapping wing design, streamlines aerodynamic efficiency, which challenges the wings to be adaptive to specific kinematics and dynamics for desirable flight. Therefore, bionic flapping wing vehicles value wings that are characterized by elevated specific strength, reduced stiffness, and lower resistance to deformation, thereby fostering flexibility and passive adaptive washout control. In contrast, fixed wings typically have rigid structural elements, such as ribs and spars, to support aerodynamic loads and curb aeroelastic instabilities.

2.1.3.4 Energy Storage and Propulsion Systems

System integration is a major challenge for bio-inspired FW-MAVs due to limited space and weight constraints. For example, the integration of sensors and signal processing units in FW-MAVs necessitates accommodating them within a confined volume with restricted weight, all while striving to minimize power consumption. This is crucial as additional weight contributes to increased power usage.

Existing MAVs exhibit propulsion system mass fractions approximately equivalent to 60% of the gross takeoff weight, making it difficult to scale down energy storage and propulsion while maintaining performance. Power consumption of actuation and communication systems is critical, with the latter being highly dependent on factors such as distance, bit rate, and data compression. Therefore, the relative requirements for high efficiency and long flight endurance in bio-inspired FW-MAVs will be correspondingly high.

FW-MAVs use various energy conversion and propulsion systems, including micro-electric mechanical systems, rechargeable lithium batteries, micro fuel cells, and internal combustion engines. While numerous micro-engines suitable

for 5g-class MAVs boasting 10W power have been created, the existing FW-MAVs are still facing challenges of long endurance or hovering longer than one hour. Therefore, designers must develop reliable scaling laws for device size and make accurate assessments of the performance potential of a given-sized power system prior to constructing the vehicles. Additionally, to enhance flight efficiency, the flapping mechanism may be refined by mimicking birds that effectively utilize their pectoral and supracoracoideus muscles, constituting roughly 16% of their body mass, to operate their wings. The combination of the bird wing's elasticity and low inertia with a significant muscle mass fraction imparts the necessary power and lift-to-weight ratio for flight within low Reynolds number regimes.

2.2 Aerodynamic Performance of Flapping Wing Rotor

2.2.1 Flapping Flight in Nature

Fixed wing aircraft are simple compared to the complex structure and unsteady fluid dynamics of flapping wing aircraft. Natural flight encompasses not only forward motion with respect to the air but also incorporates flapping, plunging, and sweeping movements (Goslow et al., 1990; Norberg, 1990). Birds employ systematic wing twisting to produce aerodynamic effects akin to ailerons found in fixed-wing aircraft, enabling rolling by varying twisting angles between wings. Birds rely on intricate muscle and bone movements to deform and twist wings during flight. Pigeons, for instance, modify wing camber and thickness along the span-wise direction (Norberg, 1990). Bats exhibit leading-edge flaps and passive camber adaptation due to their bone-membrane structure (Anders, 2000), while insect wings, formed by exoskeleton membrane outgrowths and reinforced by longitudinal veins or flexible thorax with internal muscles, undergo passive deformation in response to aerodynamic and inertia forces (Shyy et al., 2011).

Birds, bats, and insects employ diverse flapping patterns during forward flight and hovering, generating lift and thrust through varying wingtip paths (Shyy et al., 2011), as shown in Figure 2-3. Large birds exhibit relatively uncomplicated wingtip paths, such as the oval-shaped trajectory of albatrosses and figure-eight

pattern of pigeons. Conversely, small insect flyers, like locusts and beetles, display complex and highly curved wingtip paths.

Figure 2-4 shows a typical wingbeat cycle comprising four stages: downstroke, supination, upstroke, and pronation. Both the downstroke and upstroke involve translational movements that transition the wing between its posterior and anterior positions. Supination and pronation denote rapid rotations at the culmination of the downstroke and upstroke, respectively. At these reversal points, the wing undergoes rotation around a longitudinal axis to maintain a positive AoA during subsequent translational phases.

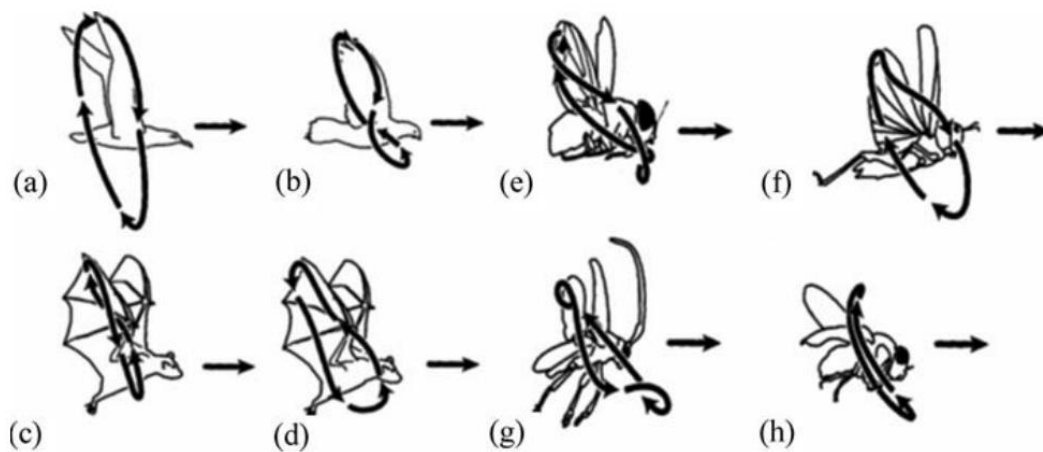


Figure 2-3 Distinct wingtip paths for flapping cycles in relation to body types among various flying species (Shyy *et al.*, 2011): (a) albatross, fast forward flight; (b) pigeon, slow forward flight; (c) bat, fast flight; (d) bat, slow flight; (e) blowfly; (f) locust; (g) beetle; (h) fruit fly.

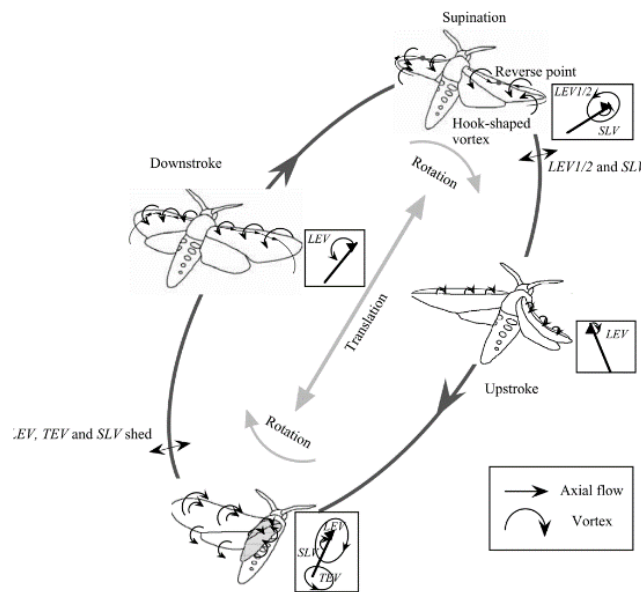


Figure 2-4 Typical insect flapping cycle (Liu et al., 1998)

2.2.1.1 Hovering

The ability of flying animals to hover is contingent upon various factors, including size, wing moment of inertia, degrees of freedom in movement, and wing morphology. Primarily, smaller birds and insects hover, while larger birds remain aloft briefly using incoming wind to generate sufficient. Hovering can be classified into two types: symmetric hovering and asymmetric hovering.

Asymmetric hovering is also known as 'avian stroke'. Large birds can only flap their wings up and down but cannot rotate forward and backward. During downstrokes, wings extend to produce increased lift, while upstrokes involve flexing the wings' outer part backward and rotating tip feathers for air passage, minimizing drag and inertia moment.

Symmetric hovering, known as true hovering or 'insect stroke,' is exhibited by insects performing symmetric up and downstrokes with a figure-eight wingtip path. This flapping pattern can be divided into horizontal and vertical strokes, as shown in Figure 2-5. Insects like fruit flies, hawkmoths, and bumblebees execute horizontal wing flapping during flight, resulting in symmetrical pitching variation and corresponding AoAs during up and downstrokes. Conversely, insects like dragonflies employ inclined or vertical flapping strokes to generate lift and thrust.

These insects exhibit asymmetrical pitching angles, resulting in different AoAs during up and downstrokes.

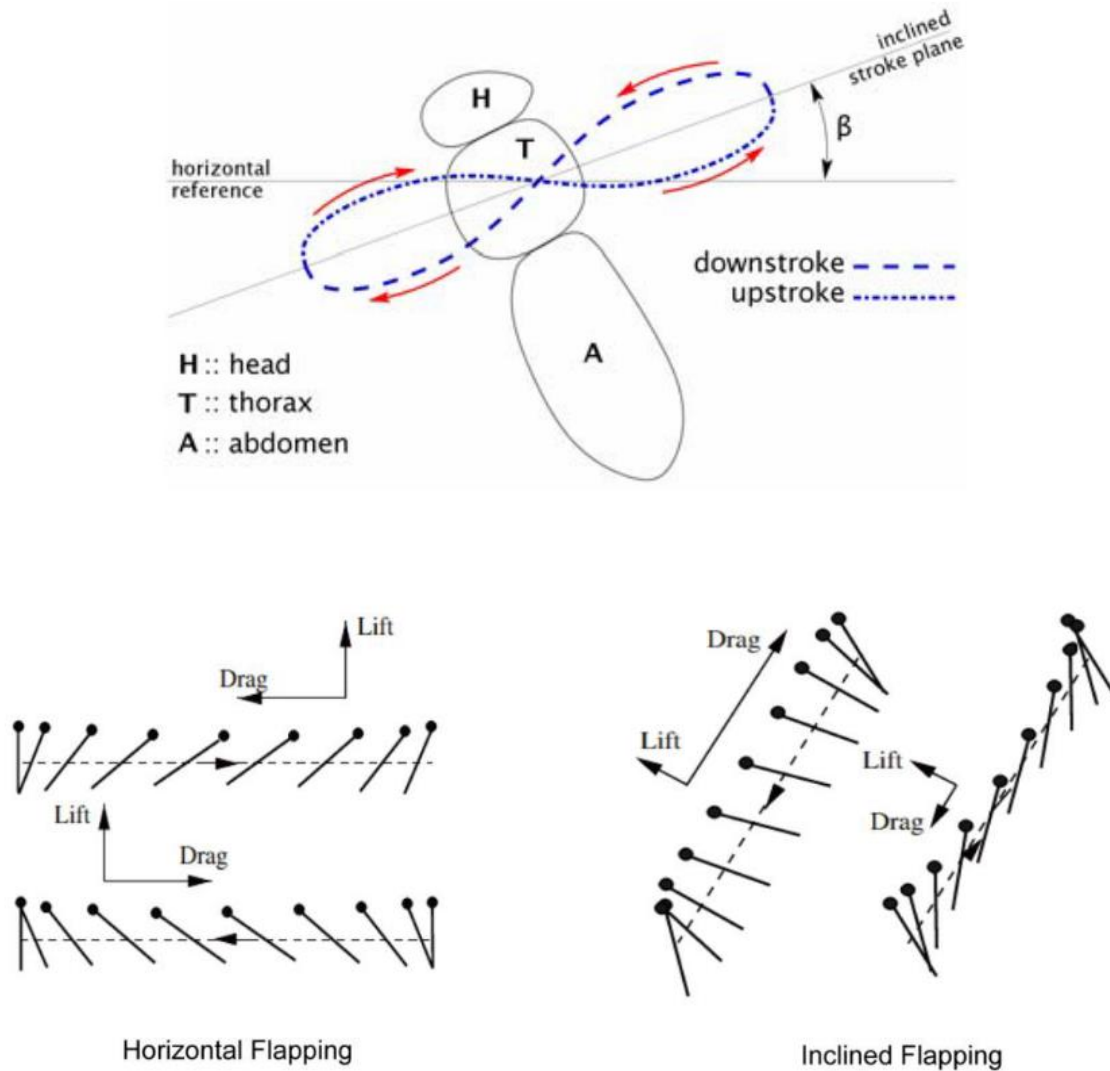


Figure 2-5 Insect stroke in hovering (Knowles *et al.*, 2007)

2.2.1.2 Forward Flight

In forward flight, a crucial parameter for indicating the aerodynamic performance of a biological flyer is the reduced frequency. It is defined as the ratio between forward velocity and flapping velocity, i.e., $k = \omega c / (2U_{ref})$, where ω is the flapping angular velocity, c is the wing's chord, and U_{ref} is the reference velocity corresponds to the forward flight velocity of the flyer in this case. During slow

forward flight, increased reduced frequency and wing-stroke amplitude result in highly unsteady flow structures. In contrast, fast forward flight exhibits lower reduced frequency and flapping amplitude. Based on the reduced frequency magnitude, lift and thrust produced by flapping motion can be assessed using either quasi-steady or unsteady methods.

Aerodynamic force generation varies along the wingspan, with the relative flow velocity U_r used to describe these forces, defined in vector notation as $U_r = U + U_f + w_i$, where U is the forward velocity of the flyer, U_f is the flapping velocity, and w_i is the downwash velocity that can be neglected in fast forward flight.

Figure 2-6 demonstrates that the resultant aerodynamic force is directed forward, generating lift and thrust at the wingtip, while pointing backward at the wing root, resulting in lift and drag. Tobalske and Dial (1996) observed that birds maintain constant flapping frequency during steady-speed forward flight, with the body pitching angle associated with the horizontal decreasing as flight speed increases. This indicates that wing flapping motion supports weight at slow speeds and provides positive thrust at high speeds.

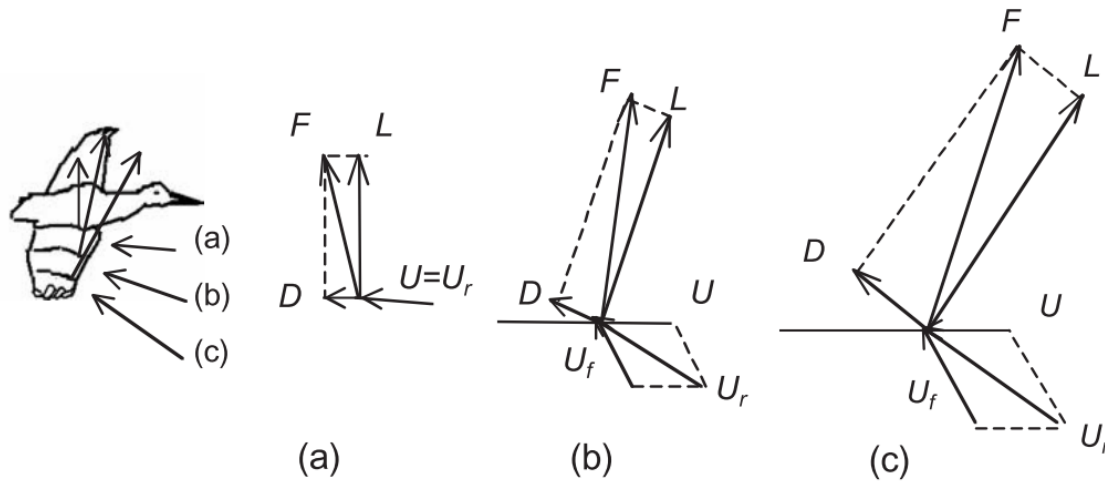


Figure 2-6 Velocity force vector diagram at different section along the span in forward flight (Knowles *et al.*, 2007).

2.2.1.3 Take-off

Short take-off and landing are significant advantages of bird-like flapping wing vehicles, making it beneficial to mimic real flying animal behaviors or bio-inspired

wing kinematics. Examining the take-off motion of butterflies can provide insights into the landing performance of flapping wing aircraft, in addition to bird performance observations.

Easily observable due to low flapping frequency, butterflies reveal typical take-off motion in Figure 2-7, as recorded by a high-speed camera. The figure highlights the relationship between instantaneous flapping angle, body pitching angle, and trajectory throughout the take-off process. The flapping frequency was 10 Hz, with a downstroke lasting 65 milliseconds and upstroke 35 milliseconds, resulting in a 1.5 down-to-up stroke ratio. This figure also indicates that body pitch angles, consistently positive, resemble bird take-offs, where an initial impulse is generated through high-angle wing motion to achieve the minimum required lift. It can be assumed that adjusting the stroke cycle ratio influences the body pitching angle, thereby impacting the posture. Moreover, certain comparative computational fluid dynamics (CFD) simulations have unveiled the pressure generated during butterfly flapping motion, along with aerodynamic forces stemming from unsteady airflow and vortex formation.

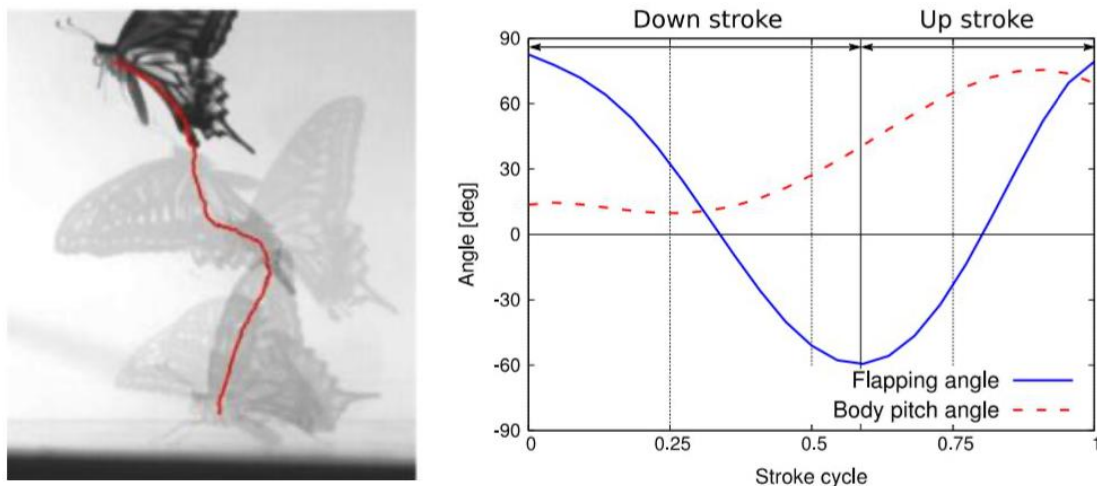


Figure 2-7 Butterfly trajectory, flapping, and body pitching angles during take-off stage (Fujikawa *et al.*, 2009).

2.2.1.4 Landing

Birds exhibit remarkable landing efficiency, adept at executing complex landings on various surfaces, including ground, water, tree branches, and power lines.

They rapidly land, enter a stall, abruptly reduce their velocity to zero, and seamlessly adjust to various surfaces, such as land, water, or even perching on barely visible wires. Birds typically approach landing points by decelerating and losing kinetic energy, with two distinct approach patterns. One involves a slow, smooth descent along a curvilinear path in case of injury but requires significant physical exertion. The alternative is a high-velocity approach with a high AoA and horizontal deceleration at the peak moment just before touchdown, resulting in a swift, energy-saving landing with a straight trajectory tangent to the ground.

Figure 2-8(a) demonstrates Diamond Doves altering body angles during the landing process. They extend their legs and adopt a high angle of attack (AoA) of up to 75° as they approach the ground. In Figure 2-8(b), two types of bird landings are depicted, with circular black and white markings representing the horizontal and vertical components, respectively. The high-energy, smooth landing trajectory is distinguished by a progressive deceleration in horizontal velocity and a consistent elevation in body angle. Conversely, a rapid approach to the earth with a high kinetic energy entails vigorous wing flapping, negative horizontal acceleration, and a decrease in both horizontal and vertical speeds. Simultaneously, the nose rises, leading AoA to increase linearly in a short time, characterizing this landing mode. This insight suggests that generating more lift and drag can enhance the landing performance of flapping wing aircraft. Additionally, certain bird species can approach at a high AoA up to approximately 90° . Researchers from Stanford University demonstrated that "propulsion is not necessary for high-performance perching" (Reichhardt, 2014). Using a straightforward actuator at the trailing edge, they fabricated a glider capable of effectively approaching a wire situated over 10 feet away. During the approach, the glider's AoA nearly reached 90° .

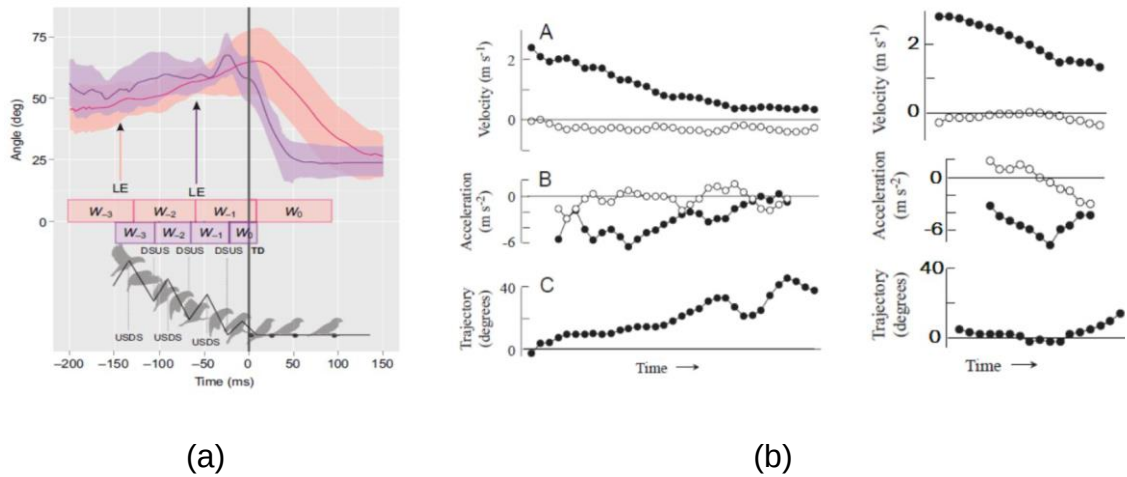
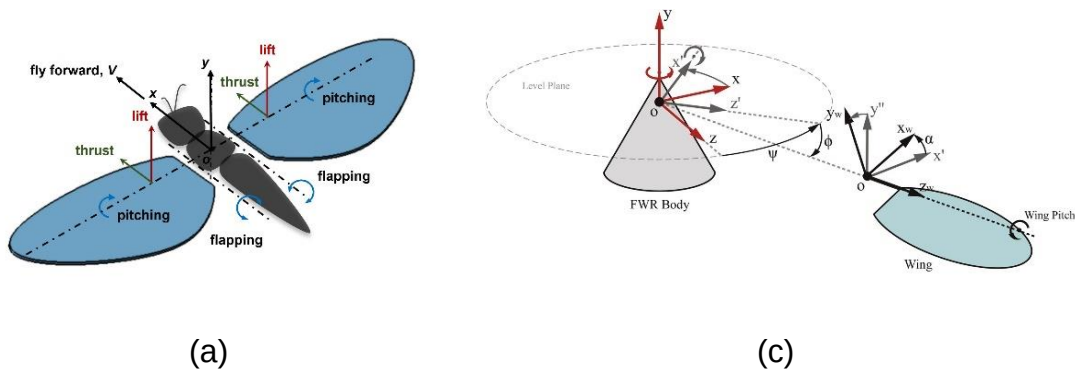


Figure 2-8 (a) Attack of angle of diamond dove bird during landing (orange) ; (b) Smooth landing (left) and sharp landing (right) (Camacho & Henriques, 2017).

2.2.2 FWR Kinematics of Motion

2.2.2.1 Wing Kinematics Definition

The readily observed flapping flight of birds and insects produces lift and thrust simultaneously, but their kinematics of flapping motion can be different. With the exception of small birds like hummingbirds, most birds execute a nearly vertical stroke plane during cruise flight, characterized by a relatively low flapping frequency and asymmetric up and downstrokes (Biewener & Patek, 2018; Alexander, 2002). In contrast, most insects flap their wings in a nearly horizontal stroke plane with a higher frequency and symmetric fore and back strokes during hovering, while most birds are incapable. As insects engage in forward flight, their stroke plane gradually inclines forward (Sane, 2003).



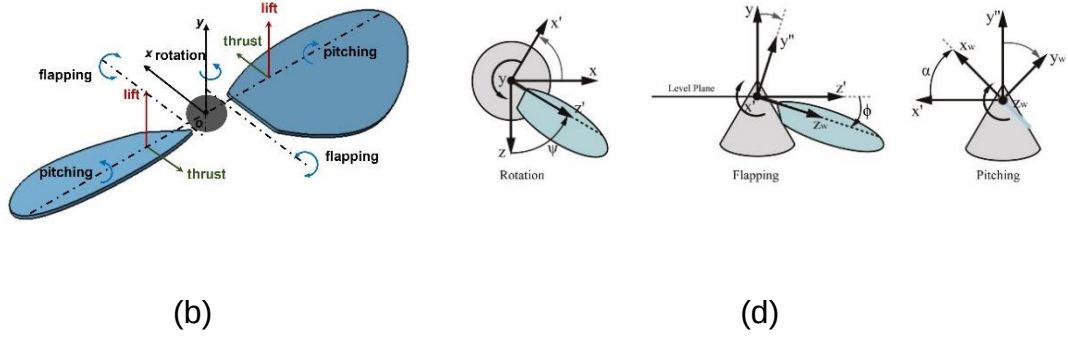


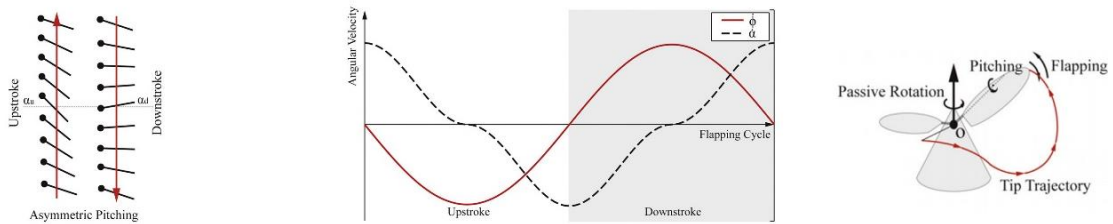
Figure 2-9 (a) Sketch of insect forward flight; (b) FWR concept of hovering; (c) Coordinate system and rotation angles definitions for FWR wing, and (d) Top, back and side view of the Euler angles (Li et al., 2017).

As illustrated in Figure 2-9(a), a pair of insect wings arranged symmetrically about the x -axis produces lift in the y -axis and also thrust in the x -axis for forward flight (Salami et al., 2019; Ward et al., 2015). By reversing one of the wings in the opposite direction, the pair of wings becomes axially symmetric about the vertical y -axis or an asymmetrical arrangement about the x -axis like a rotary wing, as illustrated in Figure 2-9(b). The flapping wings still generate lift in the y -axis, but the associated thrust from the two wings generates a torque about the y -axis instead of a force in the same direction. When the wings are driven only in flapping motion (upstroke and downstroke), thrust will propel themselves to rotate due to the torque in a passive manner. Unlike a rotary wing, the flapping wing rotation is self-propelled without input torque from external power; hence, there is no need for additional input power to balance the torque. This leads to the FWR design concept with a simple and power-efficient configuration.

The FWR kinematics of motion presented in a coordinate system used in previous research (Li et al., 2017) are shown in Figure 2-9(c), including the inertial system (x, y, z) fixed to the body, the wing-fixed system (x_w, y_w, z_w) fixed to the wing root, and the intermediate frame of the Euler rotations (x', y', z') and (x'', y'', z'') . The inertial system (x, y, z) and the wing-fixed system (x_w, y_w, z_w) share the same origin o , which is a fixed point at the wing root. The overlapping axes of the intermediate frames y' , x'' , and z'' are omitted for clarity. The rotating motion is in the x - z horizontal plane. The motion of the FWR is described by sequential

rotation about the y -axis (positively anticlockwise), flapping about x , and pitching about z_w axes, with the corresponding Euler angles denoted by ψ (the angle between axes ox and ox'), ϕ (the angle between axes oz' and oz_w) and α (the angle between axes ox' and ox_w) respectively. A planar view with respect to each axis is shown in Figure 2-9(d).

The FWR kinematics of motion combine flapping, pitching, and rotating angles and amplitudes, which are normally simplified to a sinusoidal motion with a constant rotation speed in most research. Experimental measurements conducted on a mechanical FWR indicate that the wing rotation speed remains approximately constant when subjected to a predetermined input of flapping and pitching kinematics (Wu et al., 2017). Thus, the wing flapping velocity, $\dot{\phi}$, can be represented by a function, $\dot{\phi} = \pi f \Phi \cos(2\pi \hat{t} + \pi/2)$, where f is the flapping frequency, Φ is the flapping amplitude, and $\hat{t}$ is the non-dimensional time ($\hat{t} = ft$, where t is real time). In a previous study by Li and Guo (2017), an asymmetric pitching motion inspired by dragonfly wings was employed by modulating the sinusoidal function. The pitching velocity of the wing, $\dot{\alpha}$, is given as, $\dot{\alpha} = 2f(\alpha_u - \alpha_d) \{ (-1)^{[2\hat{t}+0.5]} - \cos(4\pi \hat{t} + [2\hat{t} - 0.5]\pi) \}$, where α_u and α_d are the geometric Angles of Attack (AoA) of the wing at mid-upstroke and mid-downstroke respectively. Similarly, Wu et al. (2016) manipulated the pitching motion by using a trapezoidal function, with a non-dimensional time $\hat{t}_r$ when reverse starts and a non-dimensional reversal time interval $\Delta \hat{t}_r$ that takes for the AoA changing from α_u to α_d . The corresponding angular velocity, $\dot{\alpha}$, was modelled as: $\dot{\alpha} = 360f \{ 1 - \cos[2\pi(\hat{t} - \hat{t}_r)/\Delta \hat{t}_r] \}$. The wing kinematics resulting from these two different pitching patterns are shown in Figure 2-10.



(a)

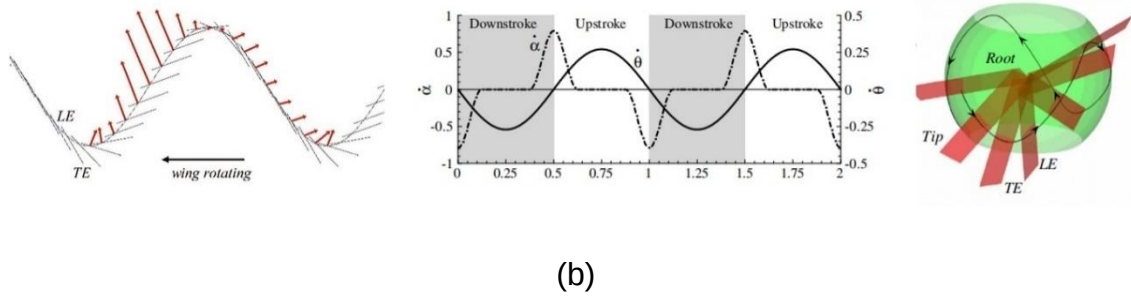


Figure 2-10 The FWR kinematics adapted from (a) the study (Li et al., 2017) and the study (b) (Wu et al., 2016).

2.2.2.2 Experimental Measurement of Wing Kinematics

Researchers used various measurement methods to collect data on the FWR kinematics of motion and unsteady aerodynamic forces for validation of the aerodynamic numerical model and optimization of the FWR mechanism. A laser sensor/velocimeter with reflective stickers was utilized to measure the flapping frequency and rotation speed of an FWR model (Guo et al., 2012; Zhou et al., 2014; Chen et al., 2020), as shown in Figure 2-11. The model was installed on a force transducer/load cell, and the data was processed through a signal amplifier and a PC to obtain the vertical force generated by the wings.

Figure 2-12 illustrates the use of a high-speed camera to capture the instantaneous images depicting the FWR kinematics of motion, including the flapping, pitching angles and wing deformation throughout multiple consecutive flapping cycles (Guo et al., 2018). The experimental outcomes substantiate that the flapping frequency, rotation speed, and time-average lift exhibit an almost linear increase with the input power. The rotation speed varies approximately linearly with the flapping frequency. Due to the aeroelastic coupling between the wing elastic, inertia, and aerodynamic forces, the wing pitching angle varies around the initial geometric AoA (15°).

Wu et al. (2013, 2017) used two synchronized high-speed cameras to capture the motion images and rebuild the position of the FWR, as shown in Figure 2-13. Their experiment prevented imaging distortion in the 3-DOF motion. The wing surface was marked, and a program was used to automatically detect and match the marked points between the two cameras, allowing for the determination of the

wing position, orientation, and deformation. Their practical FWR model showed that the flapping angular speed time history follows an approximate trapezoidal function, particularly at the beginning of flapping cycles, but fluctuates during subsequent upstroke/downstroke reversal motion. The aeroelastic effect causes passive pitching of the wings, resulting in significant variation in the pitch angle during a flapping cycle. The pitch angle reaches several peaks at the reversal and the middle of the upstroke/downstroke.

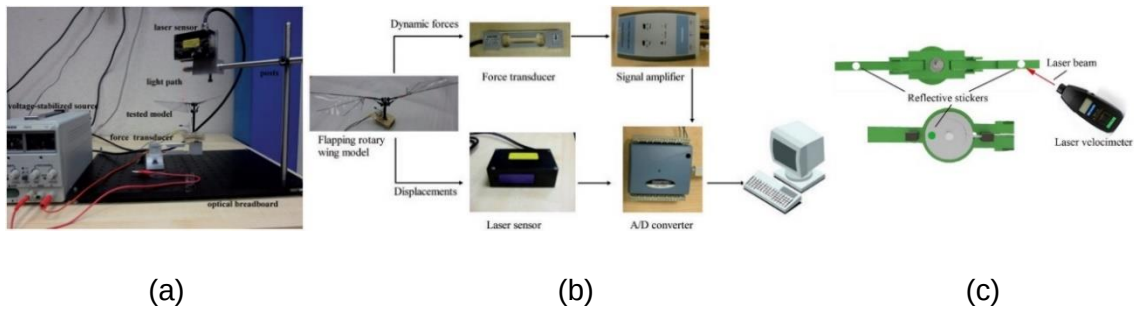


Figure 2-11 Experiment setup and measurement circuits for an FWR model [28]: (a) laser sensors and (b) load cells; (c) rotation speed and flapping frequency measurement (Chen et al., 2020).

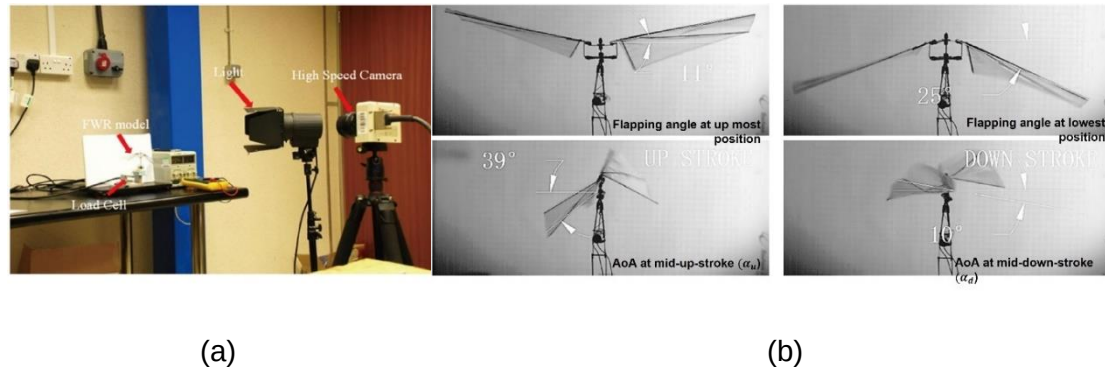


Figure 2-12 (a) FWR experiment setup using a high-speed camera; (b) Images of instantaneous moments with post-processed flapping angle and AoA (Guo et al., 2018).

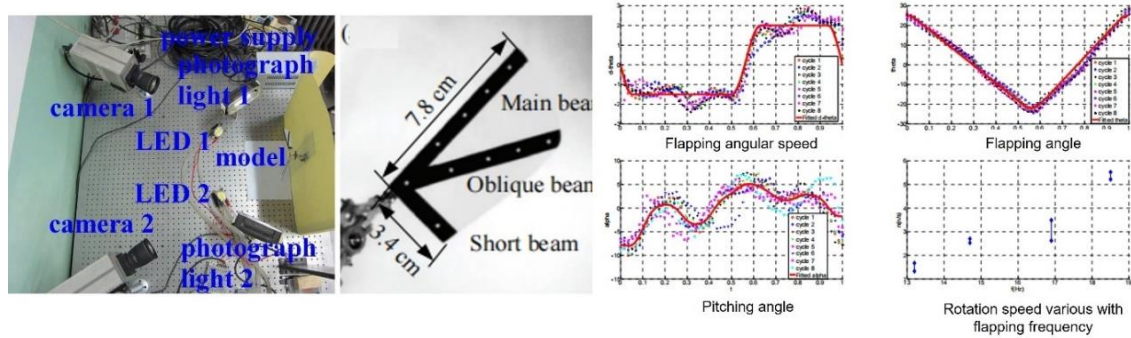


Figure 2-13 FWR test platform using two synchronized high-speed cameras and the marked points on the wing (Wu et al., 2013; 2017).

2.2.3 FWR Aerodynamic Mechanism

Airborne flapping wings generate unsteady aerodynamic forces, with two main types of kinematics: horizontal and vertical strokes. Many insects, such as hummingbirds, fruit flies, and bumblebees, use a figure-of-eight motion track in a horizontal plane with symmetric wing pitching and identical angles of attack in VTOL and hovering (Zhu et al., 2022; Wang, 2004), as shown in Figure 2-14(a). Their mechanism involves stall delay due to an attached leading edge vortex (LEV), contribution from added mass and rotational circulation, wing-wake interaction, and the clap-and-fling effect (Sane, 2003; Phan & Park, 2019).

The FWR employs unique kinematics of motion, with flapping up and down strokes and wing rotation, as shown in Figure 2-9 and Figure 2-14(b). Figure 2-14(b) demonstrates that similar to insect flapping wings, the LEV attachment is crucial for FWR to generate high lift. During downstroke, a substantial wing vortex ring comprising the LEV, trailing edge vortex (TEV), and tip vortex (TV) is formed, dominating lift production, as illustrated in Figure 2-14(c). The main difference between the FWR and insect-like flapping wings is the rotation-induced airflow, which alters the direction and acceleration of incoming velocity, thereby adjusting the effective AoA and improving aerodynamic lift and efficiency. Further insights into this aspect are detailed in the following section.

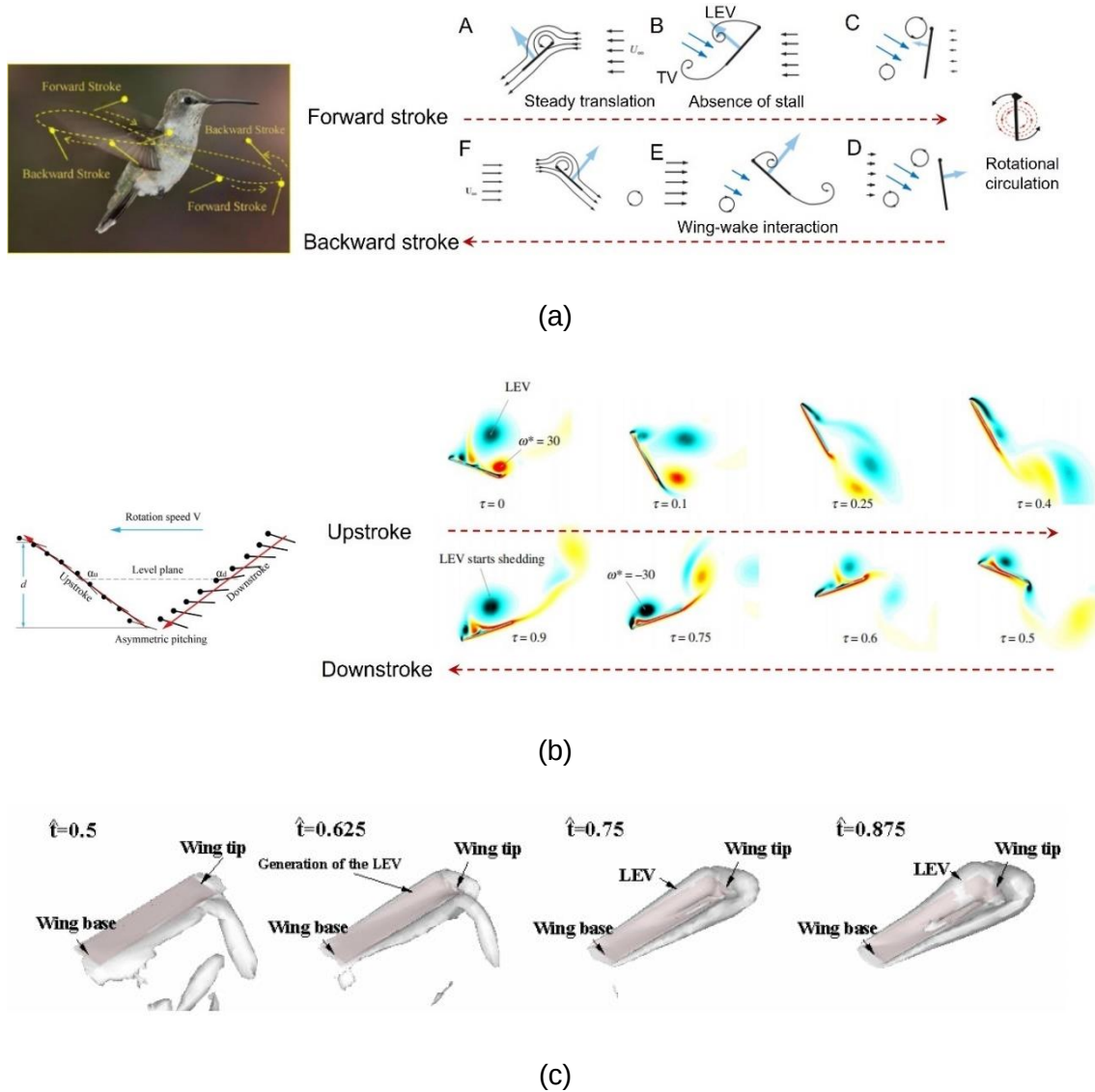


Figure 2-14 (a) Hummingbird flight pattern (Zhu *et al.*, 2022) and unsteady aerodynamic mechanisms of insect flight (Sane, 2003); (b) Contour of flow vorticity for the 2D wing section of the FWR (Guo *et al.*, 2018; Li & Guo, 2018); (c) Variation of the flow field around the 3D FWR wing in downstroke (Wang *et al.*, 2013).

2.2.3.1 High Lift Mechanism of LEV

Researchers often employ the computational fluid dynamics (CFD) method to simulate and depict the structure of the flow field around the wing in detail, as well as the evolution of vortex and wake, based on incompressible unsteady Navier-Stokes equations. For the FWR, the flow crossing a 2D wing chord exhibits a dynamic history of vortex generation and shedding, as shown in Figure 2-14(b) (Li & Guo, 2018). As the FWR flaps up and down, the vortex on the leading edge

is developed and shed over one cycle after another. The LEV is lost near the end of the downstroke, resulting in a drop in the lift coefficient. The maximum rotation speed is achieved when the wing generates small and symmetric LEVs both the upstroke and downstroke. However, the larger and asymmetric LEV generated during the downstroke is advantageous for lift production but decreases propulsive efficiency (Li & Guo, 2018).

The positioning of the LEV on either the upper or lower wing surface of the FWR is contingent upon the effective AoA (Wu et al., 2015). A strong LEV for high lift production usually forms on the upper surface of the wing and continues to shed until a reverse flow emerges from the trailing edge. The size of the LEV increases as the effective AoA increases and reaches its peak near the middle of the upstroke or downstroke. Furthermore, the effective AoA can keep positive with the LEV generated on the upper wing surface during the upstroke, owing to higher lift production than the vertical flapping wing (Wu et al., 2016). Finally, the pitching motion intensifies the leading edge vortex, resulting in more aerodynamic force projection in the direction of lift (Chen et al., 2018).

2.2.3.2 Kinematic Effects on FWR Aerodynamics

Several numerical methods, including CFD simulation (Wu et al., 2015, 2016, 2021; Li et al., 2017, 2018; Wang et al., 2018; Zhou et al., 2018) and experimental work (Chen et al., 2021; Guo et al., 2009, 2012; Long et al., 2015; Zhou et al., 2014), have been carried out to study the effect of wing kinematic of motion and mechanical and geometric parameters on the aerodynamics of FWR.

Li and Guo (2017) adapted a quasi-steady aerodynamic model that considers both translational and rotational effects to predict the time course of FWR aerodynamic forces. The model assumes that fluid dynamic force depends only on the instantaneous wing motion, including velocity and acceleration. Time-invariant parameters such as translational force coefficients are determined empirically based on the wing geometry and flow conditions, such as Re . The elementary forces along the wingspan are integrated to calculate the total force and torque of a 3D wing based on the 2D flapping wing theory. The lift and rotational moment (torque) coefficients of the FWR are computed as $C_L =$

$L/(0.5\rho U^2 S)$ and $C_M = M/(0.5\rho U^2 S \bar{c})$, where ρ is the air density, U is equal to $2\Phi f R_2$ with the radius of the second area moment R_2 , S is the wing area and $\bar{c}$ is the mean chord length. A non-dimensional rotation speed, $\eta = \psi_0/(2\Phi f)$ where ψ_0 is the wing rotation speed in the horizontal plane, is used to indicate the deflection of the effective AoA (α_e).

Li and Guo (2017) focused on investigating the effect of the FWR pitching angle on the aerodynamic forces, in an equilibrium state when a constant rotation speed and average rotational moment (torque) coefficient $\bar{C}_M = 0$ conditions are reached. During downstroke, the wing forms a large effective AoA (α_e), contributing to a large lift and rotational moment, while during upstroke, it forms a small positive effective AoA (α_e), generating a small lift and anti-rotating moment, as shown in Figure 2-15(a). A larger rotation speed (η) in an equilibrium state is associated with a smaller effective (α_e) during up and down stroke (specifically its peak value at $\alpha_u = 9^\circ$ and $\alpha_d = -9^\circ$) but a larger mean lift coefficient ($\bar{C}_L$), as shown in Figure 2-15(b). Zhao et al. (2018) also found that selecting a small pitching amplitude ($\Delta\alpha = \alpha_u - \alpha_d$) of less than 20° and a mean AoA ($\alpha_0 = (\alpha_u + \alpha_d)/2$) of about 40° is beneficial for the FWR to achieve fast rotation speed and produce high lift coefficient, as shown in Figure 2-15(c).

The effects of rotation speed, flapping frequency, and AoA on the lift production of the FWR were also investigated experimentally. The rotation speed was found to increase approximately linearly with the flapping frequency as more energy was transferred to the system (Wu et al., 2017), as shown in Figure 2-16(a). The mean lift produced by the FWR also increased linearly with the flapping frequency and reached a peak value at initial AoA around 15° (Zhou et al., 2014), as shown in Figure 2-16(b). Beyond this point, the mean lift value gradually decreased but remained high until the AoA exceeded 35° , indicating the occurrence of dynamic stall, in which the wing can travel at a high AoA and generate further lift before stalling (Ellington, 1984b). This is due to the stability of the LEV which circulation augments the bound vortex and hence the lift, as characterized by the quasi-steady model of flapping wings (Li et al., 2017; Chin & Lentink, 2016).

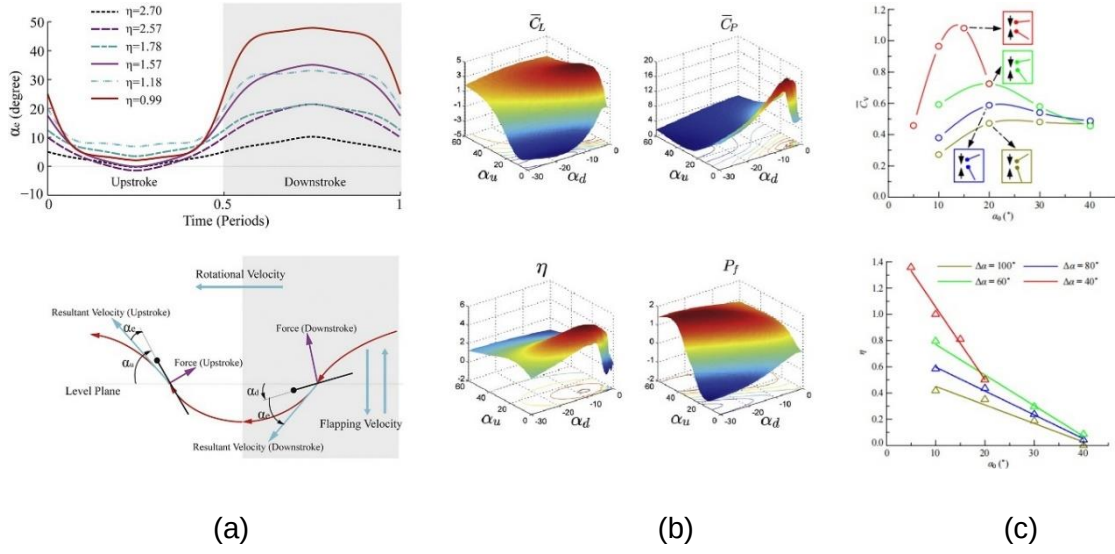


Figure 2-15 (a) Variation of the FWR effective AoA (α_e) in one flapping cycle at different rotation speeds (top) and directions of velocity and aerodynamic forces (bottom); (b) 3D surface plots of mean lift coefficient ($\bar{C}_L$), mean power coefficient ($\bar{C}_P$), nondimensional rotation speed (η), and power factor (P_f) in the ranges $\alpha_u = 0 \sim 60^\circ$ and $\alpha_d = 0 \sim 30^\circ$ (Li et al., 2017); (c) Mean lift coefficient (top) and nondimensional rotation speed (bottom) vary with the mean AoA (α_0) and the pitching amplitude AoA ($\Delta\alpha$) (Zhou et.al, 2018).

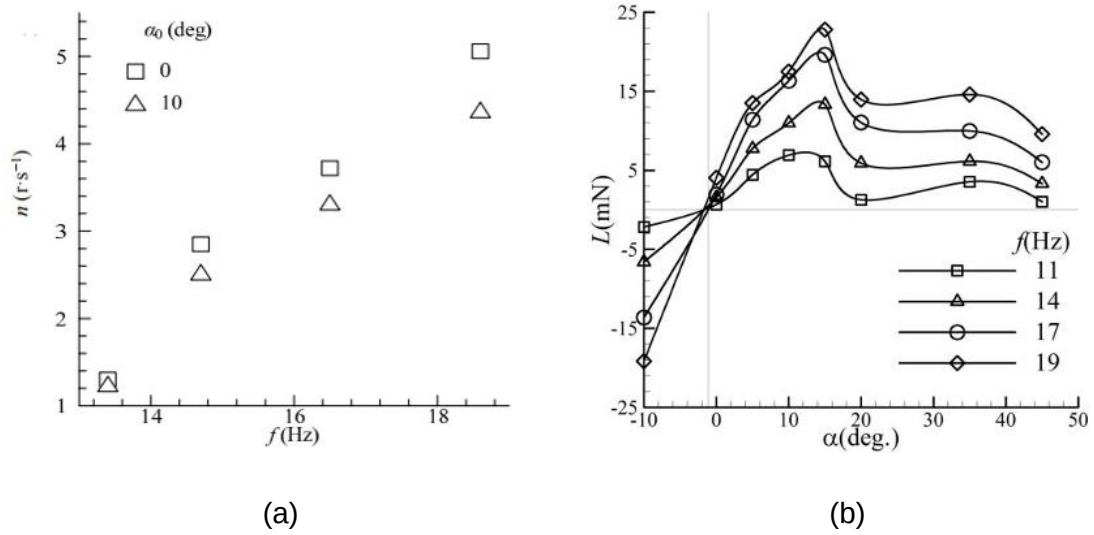


Figure 2-16 (a) Rotating speed versus flapping frequency (Wu et al., 2017); (b) Variation of lift production with initial AoA in various flapping frequencies (Zhou et al., 2014).

2.2.4 Aerodynamic Performance of FWR in Hovering and Forward Flight

2.2.4.1 FWR Hovering Flight Performance Compared with Flapping Wing and Rotary Wing

As current MAVs face limitations in payload capability and flight endurance, aerodynamic vertical force and power efficiency are two significant indexes of the performances of various wing configurations. The novel FWR-MAV has garnered interest due to its ability to couple flapping and rotation motions to enhance lift production in hovering flight. An experimental study (Zhou *et al.*, 2014) showed that the FWR generates more lift than the superposition lift from purely flapping and purely rotating motions. The lift generated by the FWR is greater than that of a conventional rotary wing at the same rotating speeds in the low Re range of 2600 to 5000, with an appropriate Strouhal number between 0.2 to 0.34.

The Strouhal number, denoted by St , is a non-dimensional parameter that characterizes the wing kinematics of motion (e.g., stroke frequency, amplitude, and forward flight), which governs the unsteady flow and the shedding of vortices. It is closely related to the propulsive efficiency, which is the ratio of the aerodynamic power output for propulsion to the power input (Taylor *et al.*, 2003; Triantafyllou *et al.*, 1993). For an FWR, high efficiency of lift production is achieved at St between 0.1 and 0.3, which is generally less than the St required for high propulsive efficiency (between 0.2 and 0.5) (Li & Guo, 2018).

The aerodynamic power efficiency of FWR is evaluated by calculating the aerodynamic power consumed to counteract the work done by the wing flapping and pitching motions at a certain equilibrium rotation speed. This indicates that the average power consumed by rotating motion becomes zero. The aerodynamic power efficiency is actually denoted by a power factor (P_f) which represents the power work for producing a certain amount of aerodynamic lift force, computed by $\bar{C}_L^{1.5} / \bar{C}_p$ where $\bar{C}_L$ is the average lift coefficient and $\bar{C}_p$ is the average aerodynamic power efficient in a flapping cycle (Li *et al.*, 2017). The aerodynamic power efficient (C_p) is given as $C_p = C_M \cdot \omega$, based on the moment coefficient (C_M) and the angular velocity vectors (ω) in inertia coordinate system

(Wu et al., 2016). A higher power factor indicates a more power-efficient system in producing the same average lift coefficient.

Generally, the criterion of maintaining a constant Re is used to compare the aerodynamic performance of various MAV configurations in hovering (Kruyt et al., 2014; Lentink & Dickinson, 2009; Wang, 2004). Li et al. (2017) and Wu et al. (2016) conducted a comparative analysis of aerodynamic force and efficiency of four types of wings (rotary wing (RW), insect-like vertical flapping wing (VFW), horizontal flapping wing (HFW), and FWR) by their average lift coefficient and power factor in the same Re (3500 and 2325, respectively). Their results demonstrate that the FWR can produce a significantly greater aerodynamic lift coefficient than other wings, as shown in Figure 2-17(a)(b). Although the RW has the highest power efficiency, its lift coefficient is the smallest, whereas the FWR offers a broader range of combinations of aerodynamic lift and power efficiency with optional kinematics of wing motions. Furthermore, for the FWR, the state of maximum lift efficiency nearly approaches the state of highest aerodynamic power efficiency.

Alternatively, without the constraint of Re , Zhou et al. (2018) compared the power consumption of RW, FW and FWR for producing a desired lift. They found that FWR and RW can achieve the target lift with less power consumption at an AoA that corresponds to the maximum lift and power coefficients. However, the most power-efficient RW is unable to produce sufficient lift when compared to the FWR at the Re around 2600, as illustrated in zone I of Figure 2-17(c), particularly at the AoA below 20° (Zhou et al., 2014).

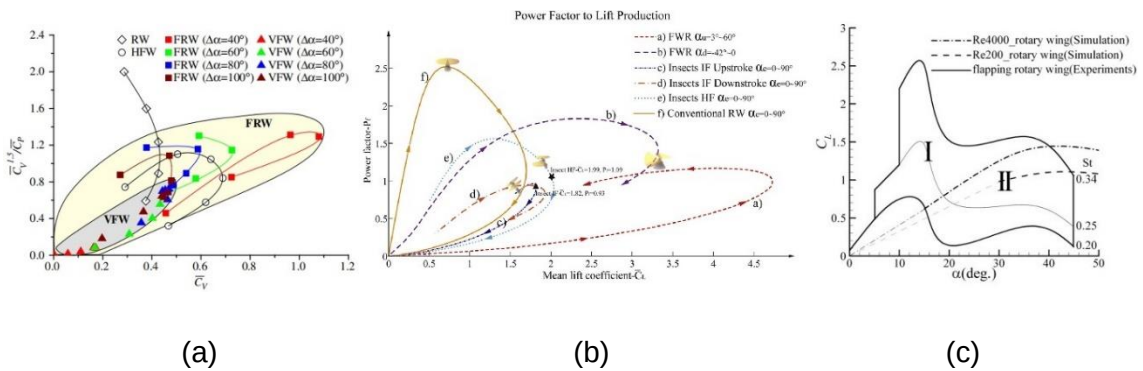


Figure 2-17 Performance polar of power factor varies with mean lift coefficient by different types of wings (a) at $Re = 2325$ (Wu et al., 2016) and (b) at $Re \sim 3500$ (Li et al., 2017); (c) Comparison of lift coefficient between FWR and RW at different Re (Zhou et al., 2014).

2.2.4.2 FWR Forward Flight Performance

Most previous studies on FWR aerodynamics have concentrated on hovering flight, which is an initial flight condition for an aircraft design. To explore practical engineering applications of FWR, Wu et al. (2021) conduct a numerical study to investigate the aerodynamic performance of an FWR in forward flight. FWR adopts a forward-tilted rotational plane to fly forward, which is inspired by rotary wings, as shown in Figure 2-18(a). They evaluated lift, thrust, rotating moment and power consumption, and discussed the differences between hovering and forward flight in terms of the rotational-cycle-average and transient aerodynamics, vortex structure, and pressure distribution on the 3D wing surface.

Similar to hovering flight, FWR in forward flight generates lift and thrust primarily during the downstroke and produces a propulsive rotation moment during the upstroke, with periodic formation and shedding of LEVs as the wing flaps up and down. When rotating at a specified rotation speed, FWR in forward flight experiences a decrease in the rotational-cycle-averaged lift and thrust, but an increase in the rotating moment compared to hovering flight.

In forward flight, FWR exhibits advancing and retreating sides similar to helicopter blades, as shown in Figure 2-18(a). The transient aerodynamics and flow pattern on the advancing side of forward flying FWR is approximately the same as those in the hover condition, while on the retreating side, a distinct vortex structure forms near the outer and inner wings at a typical upstroke stance, resulting in a reverse flow region and disappearance of the strong negative pressure area from the wing upper surface. As illustrated in Figure 2-18(b), this forms an LEV on the wing's lower surface with an area-enlarged pressure region appearing on the upper and lower surfaces, leading to a sharp reduction in lift and thrust and an enhancement of rotating moment. Consequently, the changes in aerodynamics

during forward flight compared to hovering flight are primarily due to the significant reverse flow region on the retreating side.

Wu et al. (2021) also comprehensively analysed the effects of various wing kinematics such as rotation speed, advance ratio, rotational plane forward-tilted angle and Re on the aerodynamic forces, moment, and power consumption of the forward-flying FWR. The finding showed that a moderate advance ratio and a rotational plane forward-tilted angle are crucial for aerodynamic enhancement and power saving.

Typically, FW and RW forward tilt the rotating plane by 0° to 50° in forward flight (Dickson & Dickinson, 2004; Meng & Sun, 2011), with advance ratios ranging from 0.3 to 0.5 (Dickson & Dickinson, 2004) and 0.1 to 0.7 (Meng & Sun, 2011; Nagai & Isogai, 2011), respectively. A forward-tilted rotating plane will project additional lift in the front direction, converting partial lift to thrust. When the FWR operates at a stable passive rotation speed with near-zero rotational moment ($\bar{C}_M = 0$), lift, thrust, and power consumption remain nearly unchanged while the advance speed is increased in small advance ratios below 0.6. It can be seen that thrust production of the FWR no longer causes lift loss, and thus, additional control of wing kinematics is no longer required to increase lift to balance the vehicle weight. This differs from purely FW and RW in hovering flight and potentially reduces the difficulty of designing control systems.

FWR can rotate faster at a large rotating plane forward tilted angle, improving lift and thrust production, but if the tilted angle exceeds 30° , thrust no longer increases and there is a loss of lift. The generated lift can remain larger than in hovering when the tilted angle is lower than 30° , allowing for relatively low power consumption. Hence, a rotating plane with a forward tilted angle of around 30° is recommended for FWR to achieve faster forward flight.

The aerodynamic performance of FWR can be fully realized at Re greater than 1000, taking advantage of a faster rotation speed to enhance aerodynamic forces. By contrast, the aerodynamic performances of purely FW and RW are not significantly sensitive to advance ratio and rotational plane forward-tilted angle,

and both effects are generally ignored at Re less than 1000. Despite this investigation of aerodynamic performance in forward flight, the flight control strategy and relevant dynamic analysis for FWR in forward flight have been underdeveloped and there remains a gap.

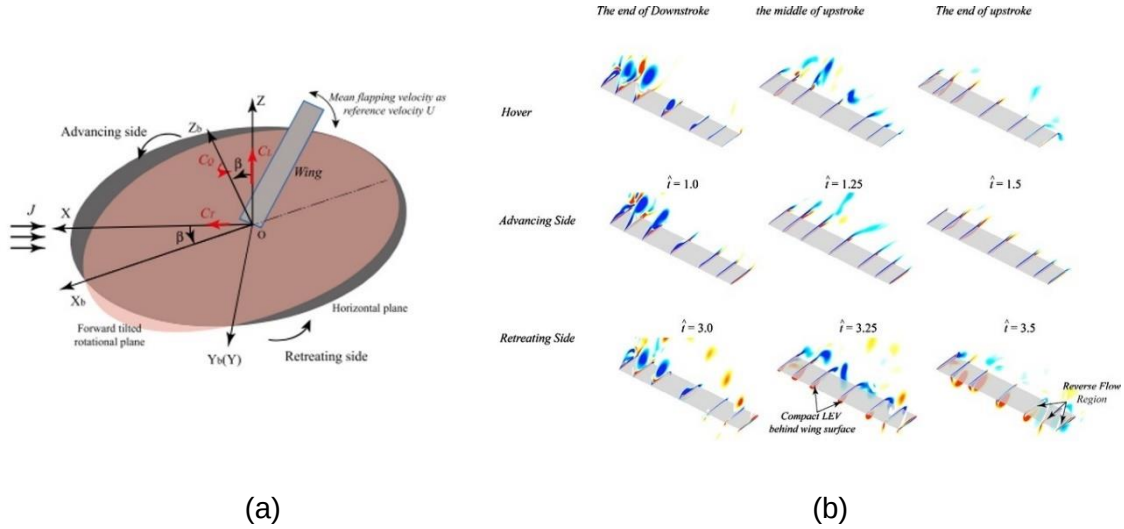


Figure 2-18 (a) Coordinate system and kinematics of FWR in forward flight ; (b) Vortex structure around the 3D wing during the upstroke of a flapping cycle in hovering flight and forward flight of FWR (Wu et al., 2021).

2.2.5 Lift Enhancement Methods

2.2.5.1 FWR Wing Geometric Optimization

Research on FWR has mainly focused on optimizing wing kinematics to improve lift production and aerodynamic efficiency. However, most theoretical and experimental analyses have relied on simple rectangular-shaped wings (Chen et al., 2018; Wu et al., 2015, 2019; Zhou et al., 2018), or on assumptions and experiences derived from insect-like flapping wings (Guo et al., 2018; Li et al., 2017a; Zhou et al., 2014). There is a need for a detailed design and analysis of wing surfaces to optimize aerodynamic characteristics and maximize FWR aerodynamic advantages. In this regard, the wing geometric parameters, including the aerofoil camber, shape of the plane surface, aspect ratio, and twist angle, are crucial design metrics as they significantly affect the aerodynamic performance of FWR.

Firstly, numerous studies of flapping wings show the importance of camber deformation in producing aerodynamic forces. Dragonflies, for example, exhibit considerable camber deformation during free flight, which plays a crucial role in generating vertical force and thrust (Wang et al., 2003). Similarly, a study on bumblebee flight has shown that a deformation of 6% camber and 20° twist can enhance lift by 10-20% and reduce the required aerodynamic power for bumblebee hovering flight by 16% (Du & Sun, 2008). By adopting appropriate camber, flapping wings can gain aeroelastic effects from asymmetric flexibility of camber variation and twist deformation to improve aerodynamic performance (Chen et al., 2018). Particularly, an additional positive camber variation in upstroke (9% camber at mid-upstroke) can reduce the negative lift during the upstroke by 22%.

Studies on the effect of camber on FWR aerodynamics have found that adopting appropriate camber can generate more lift than a planar wing (Shao et al., 2021; Wang et al., 2018). The mean lift coefficient increases as the maximum camber increases within 25% of the chord length, with the maximum lift increasing by 40%. This is because the maximum camber significantly impacts the size and strength of the LEV, which delays vortex shedding and enhances lift production. The increasing camber also affects the mean rotating moment coefficient, resulting in a significant increment.

In addition to camber design, the aerodynamic performance and flow pattern of FWR are influenced by different wing area moments (Wang et al., 2018; Li et al., 2014). The radius of the second area moment, which indicates the wing's tapered ratio between the tip and root chords, has a significant impact on the mean lift coefficient. The mean lift coefficient increases as the increasing tapered ratio enhances the LEV, whereas a large-tapered ratio results in a small mean rotating moment even as the Re increases. Therefore, Wang et al. (2018) suggested that a moderately tapered ratio forming a nearly rectangular wing is optimal for FWR.

Also, a moderate aspect ratio of 5 is recommended for FWR wing design at a low Re (Wang et al., 2018). A small aspect ratio produces high lift but low rotation

speed. In contrast, a large-aspect ratio increases rotation speed but also considerably increases the effective AoA, leading to a decrease in lift.

Increasing the twist angle of the wing plane, which is the angle between the root and tip chords of the wing, enhances the mean lift coefficient of FWR by strengthening and weakening the LEV attached above and below the wing surface during downstroke and upstroke, respectively. To balance both lift and rotating moment production, a slight positive twist angle is recommended for the FWR wing (Wang et al., 2018). This is in agreement with the design of selecting $10^{\circ}\sim 15^{\circ}$ initial AoA for FWR to improve lift at a fast rotating speed (Zhou *et al.*, 2014). Overall, the above methods of optimizing wing geometric parameters to increase lift rely primarily on the mechanism of maintaining high lift production during the downstroke and minimizing negative lift during the upstroke.

2.2.5.2 Wing Surface Bore-hole Design for FWR

An alternative method for improving lift generation in flapping wings involves creating perforations in the wing surface (Gao *et al.*, 2010). Chen et al. (2015) experimentally examined the feasibility of this solution for FWR in hovering, namely passive flow control strategy. They implemented a bore-hole design on FWR by perforating the membrane wing and covering the hole with a film that opened during the upstroke to unload negative aerodynamic force and closed during the downstroke to maintain lift generation, as shown in Figure 2-19(a). The lift enhancement achieved by the perforated wing was dependent on initial AoA, position and size of boring holes, and covering film material, resulting in a 35% increase in average lift.

Chen et al. (2022) further investigated the effect of the bore-hole design on the aerodynamics of FWR during forward flight. They found that lift enhancement of the FWR with bore-hole design could be maintained within certain limits of advance ratios and tilt angles of disk plane. The lift enhancement during upwind flapping cycles is considerably more significant than during tailwind flapping cycles. Like hovering flight, they observed a significant reduction in negative lift during the upstroke of upwind flapping cycles, attributed to the release of pressure difference and the formation of a low-pressure region on the wing's

upper surface, as shown in Figure 2-19(b). Increasing the effective angle of attack lifted the secondary LEV, which reduced the low-pressure region. However, the bore-hole design reduced the rotational torque during upwind flapping cycles. They suggest that a meticulous material and structure design for the hinge can achieve appropriate passive deformation to prompt the reduction of negative lift during upstroke.

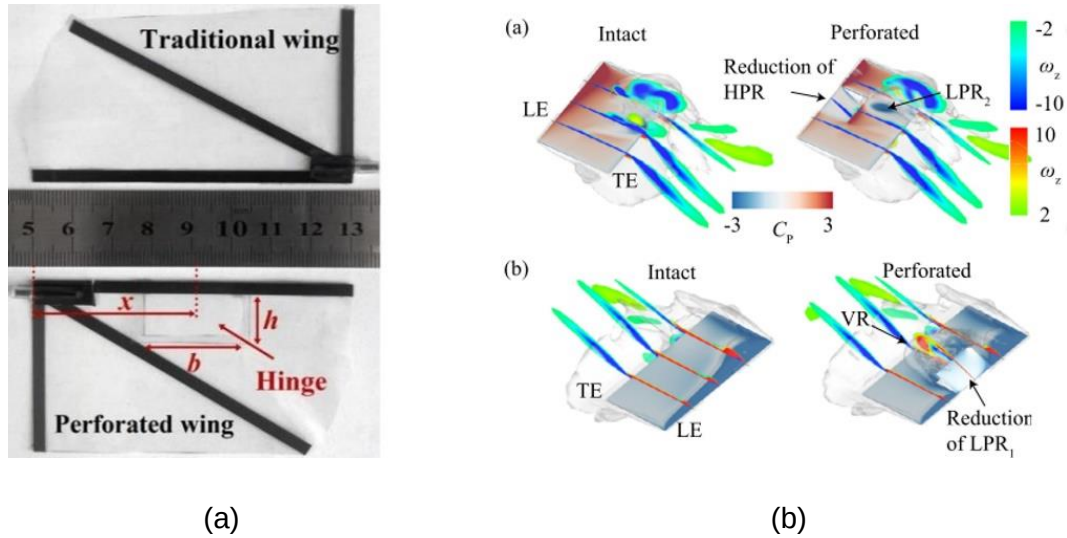


Figure 2-19 (a) A bore-hole design for FWR to increase lift (Chen et al., 2015); (b) Flow structures of intact and perforated wings in an upwind flapping cycle at the end of upstroke (Chen et al., 2022).

2.2.5.3 Twistable Flexible Wing For FWR

Flexible wings, typically made of membrane material, are commonly used in physical FW and FWR models. As the wing flaps up and down, the film and spar of the wing undergo complex aeroelastic effects, resulting in distortion. The advantages and disadvantages of a flexible wing depend on the coupling of its strength, stiffness, and deformation pattern with unsteady aerodynamics. Therefore, the effective utilization of flexible wing deformations to improve lift and efficiency and to achieve a more authentic bionic structure represents a crucial structural principle and design guideline for advancing FW and FWR design.

In fact, in most previous studies on FWR, the wings were modelled as rigid, and fewer studies have investigated the contribution of wing flexibility. Chen et al. (2022) developed a computationally efficient fluid-structure interaction (FSI)

model to investigate the effect of passive twisting of the wing on the aerodynamic performance of FWR by solving the elastic deformation of a twistable wing, as shown in Figure 2-20. Using the verified quasi-steady aerodynamic model, they identified the significant role that wing-root stiffness plays in aerodynamic performance. Their findings showed that higher wing-root stiffness values allowed the twistable wing to generate comparable lift to a rigid wing at a higher efficiency. Therefore, the stiffness design of a twistable FWR wing should be associated with its operating wing kinematics to achieve the desired aerodynamic performance. However, the performance of twistable FRWs is more sensitive to changes in flapping frequency, as an increase in frequency can significantly increase power consumption and decrease efficiency.

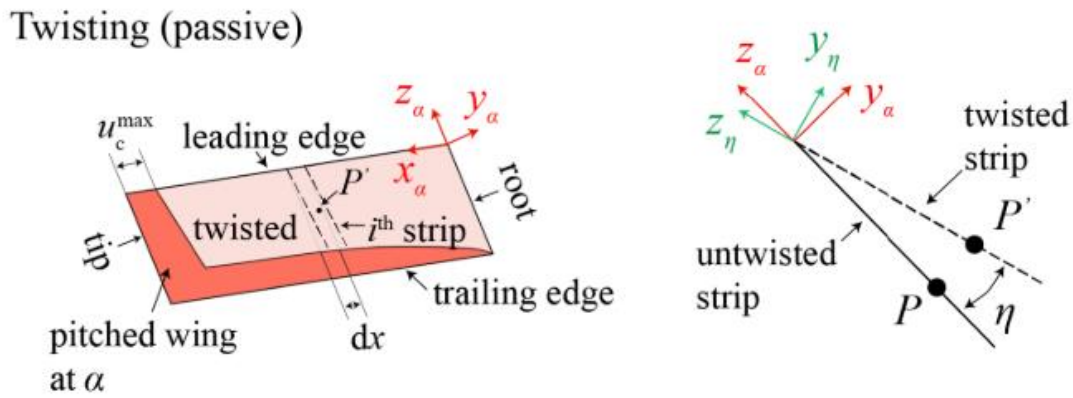


Figure 2-20 Schematic diagram of wing spanwise twisting (Chen et al., 2022).

2.3 Flyable FWR-MAVs Development

2.3.1 Mechanical FWR and Flight Test

Typically, a physical FWR model comprises a flapping-wing mechanism and a driving mechanism. A DC motor rotation is converted to linear reciprocating motion through a pushrod and transformed into wing flapping motion. The flapping-wing mechanism is a typical four-bar linkage mechanism. High-speed, low-voltage propulsive actuators such as micro-coreless and brushless motors are commonly used in FWR models. Due to the heavy load of FWR-MAV mechanisms, a gearbox is often employed to reduce motor speed and increase output torque for driving the transmission of a crank-linkage mechanism.

Guo et al. (2018) designed and manufactured the first flyable FWR model in 2014, which weighed only 2.6 g and was powered by a micromotor via fine wires. Despite its small size, it was able to generate sufficient lift force for a successful vertical take-off and remain airborne for a short period, as shown in Figure 2-21(a). During flight, the FWR had a flapping frequency of 21 Hz, a rotation speed of 7.2 rad/s, and a power consumption of 2.6 W. This achievement was a significant milestone in the research and development of FWR-MAVs, demonstrating the feasibility of the unique features of the FWR concept in terms of flight dynamics and stability.

Subsequently, Yi et al. (2017) integrated a motor with a lithium micro battery on the FWR platform, with a total weight of 21.51 g, achieving vertical take-off and upright flight with an onboard power supply for the first time, as shown in Figure 2-21(b). However, due to the lack of altitude and attitude control components and a remote or automatic system, the model quickly became unstable and fell.

Dong et al. (2020) advanced a linkage-driven three-wing FWR of 32 g with an onboard power and flight control system, as shown in Figure 2-21(c). The controlled FWR was equipped with an attitude control mechanism, including stabilizers and rudders driven by servos located below the body base. With the help of a lightweight coin-sized flight control board, the FWR successfully performed free-controlled hovering and forward flight, marking a significant milestone in the engineering development of FWR-MAVs. However, this FWR primarily relied on adding an extra wing to increase lift production to perform a free flight and did not fully highlight the aerodynamic and efficiency advantages of the FWR concept.

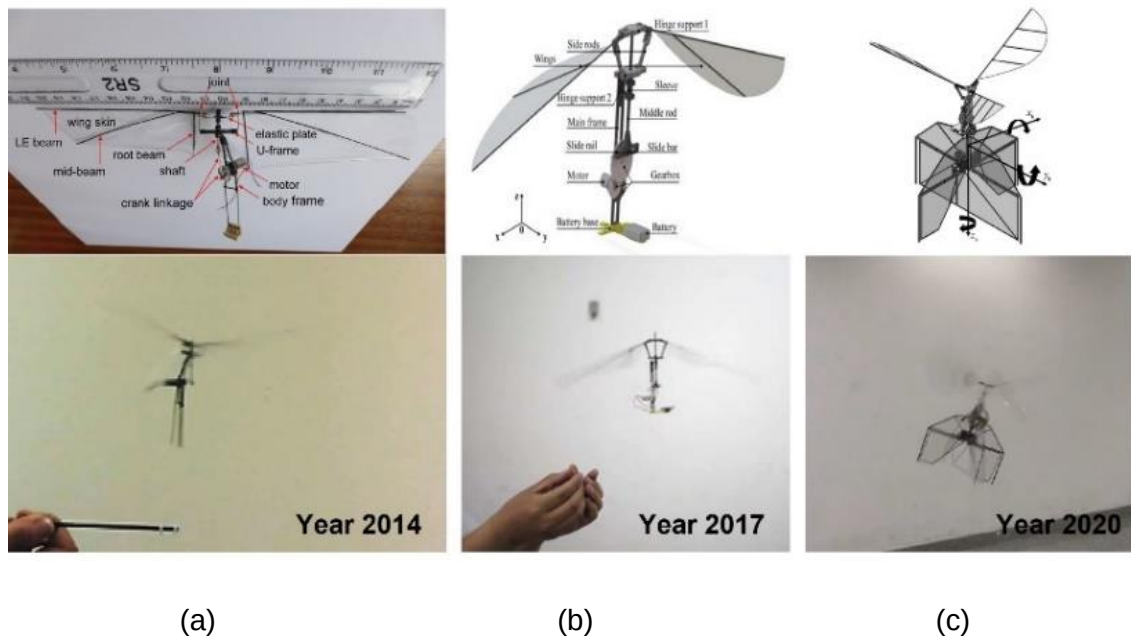


Figure 2-21 (a) First and lightest tethered flyable FWR (Guo et al., 2018); (b) First untethered flyable FWR (Yi et al., 2017); (c) A linkage-driven three-wing flyable FWR (Dong et al., 2020).

Table 2-1 Data for flyable FWR models

FWR	Wing Number	Mechanism	Weight (g)	Power Supply	Control	Flight Endurance (s)
Guo's model (Guo et al., 2018)	2	crank-slide, and linkage	2.6	coreless motor, tethered	non	-
Yi's model (Yi et al., 2017)	2	crank-slide, and linkage	21.51	coreless motor, onboard battery	non	-
Dong's model (Dong et al., 2020)	3	crank-slide, and linkage	32	brushless motor, onboard battery	free-controlled	42.5

2.3.2 Free Flight Capability and Endurance Compared with FW-MAVs

FW-MAVs are typically less than 1 m in wingspan and weigh less than 2 kg (Hassanalain & Abdelkefi, 2017). Recent advances in the research and development of FW-MAVs have been adequately summarized and discussed in earlier reviews (Petricca et al., 2011; Ward et al., 2015; Chin & Lentink, 2016; Helbling & Wood, 2018); yet, only a small fraction of the fabricated physical models in the literature can conduct the flight. The bird-tailed FW-MAVs are disregarded in this discussion due to their incapacity for hovering flight. Phan and

Park (2019) surveyed 28 insect-like tailless motor-driven FW-MAVs developed between 2005 and 2018, of which 70% were flyable. These flyable FW-MAVs were categorized based on onboard or off-board power unit and level of flight as guided take-off, tethered flight, passively stable flight, wired controlled flight, and free-controlled flight. Currently, 60% of these flyable insect-like FW-MAVs can perform controlled flight using onboard electronics and power systems, representing the greatest accomplishment in FW-MAVs research.

As depicted in Figure 2-22, recent advances in insect-inspired tailless FW-MAVs capable of free-controlled flight, sourced from reputable publications, reveal a two-wing configuration for vehicles weighing under 25 g, while those over 25 g require additional wings for adequate lift. For example, the Nano Hummingbird weighing 19 g, with two wings, boasts the longest flight endurance of 4 min for a small magnitude (< 25 g) FW-MAV (Keennon *et al.*, 2012). In contrast, the most sophisticated and representative insect-like tailless FW-MAV at a relatively large magnitude (> 25 g), the Delfly Number, weighs 28.2 g and has four wings enabling a flight time of 5 min and quick turns (Karasek *et al.*, 2018). Despite being the heaviest insect-inspired tailless FW-MAV at 62 g, the two-wing robotic hummingbird can only fly for 5 s due to a heavy load (Coleman & Benedict, 2015). It can be seen that the FW-MAVs have been facing problems of lift production and short flight endurance.

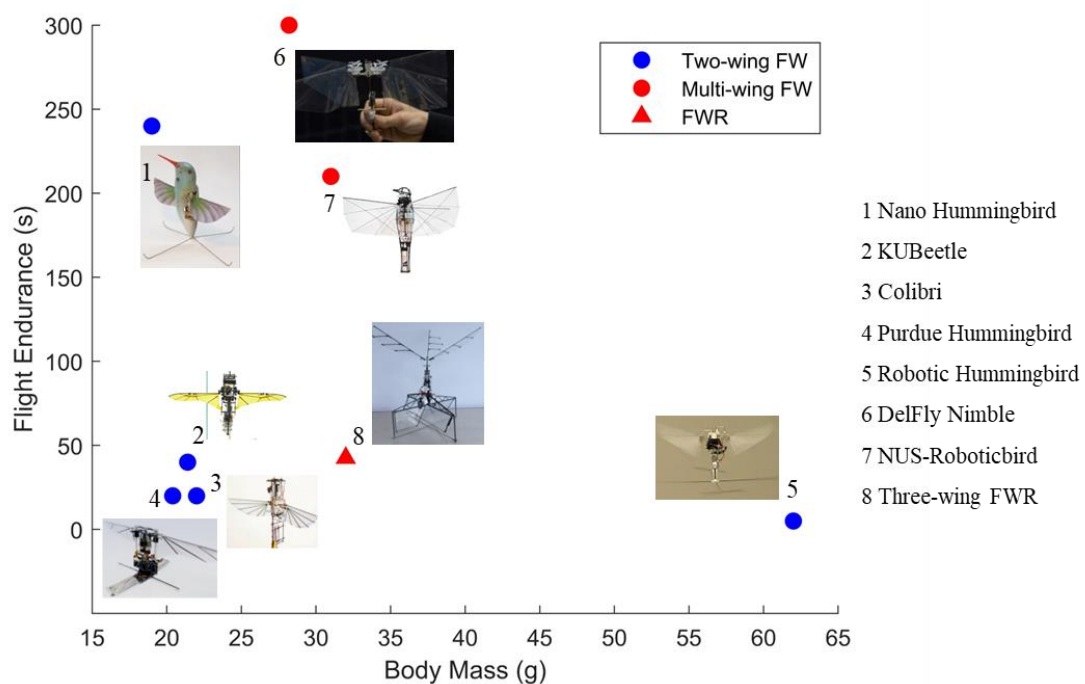


Figure 2-22 Flight endurance of free-controlled hovering, insect-inspired tailless FW-MAVs (1 (Keennon *et al.*, 2012), 2 (Phan & Park, 2020), 3 (Roshanbin *et al.*, 2017), 4 (Tu *et al.*, 2020), 5 (Coleman & Benedict, 2015), 6 (Karasek *et al.*, 2018), and 7 (Nguyen & Chan, 2019)) as well as the untethered flyable FWR-MAV (8) (Dong *et al.*, 2020).

Furthermore, when comparing body weight and size, it is evident in Figure 2-23 that heavier vehicles require longer wingspans. In addition, Purdue Hummingbird (Figure 2-23(4)), which has comparable weight and wingspan to Nano Hummingbird (Figure 2-23(1)) and KUBeetle (Figure 2-23(2)), utilizes two motors but has a shorter flight endurance of only 20 s, compared to the 4 min and 40 s of Nano Hummingbird and KUBeetle, respectively. This indicates that the aerodynamic efficiency of FW-MAVs is low since additional motors cannot effectively enhance the flight performance. Conversely, employing multiple motors in FWRs could be advantageous, given their superior aerodynamic forces and efficiency.

As the innovative amalgamation of flapping and rotary wings, the FWR has undergone rapid development in recent years in an effort to keep pace with advances in FW-MAVs. It took 5 years for the research team from the FWR

concept to achieve the first flight of a 2.6-g prototype and continuously increase the take-off weight and payload capability.

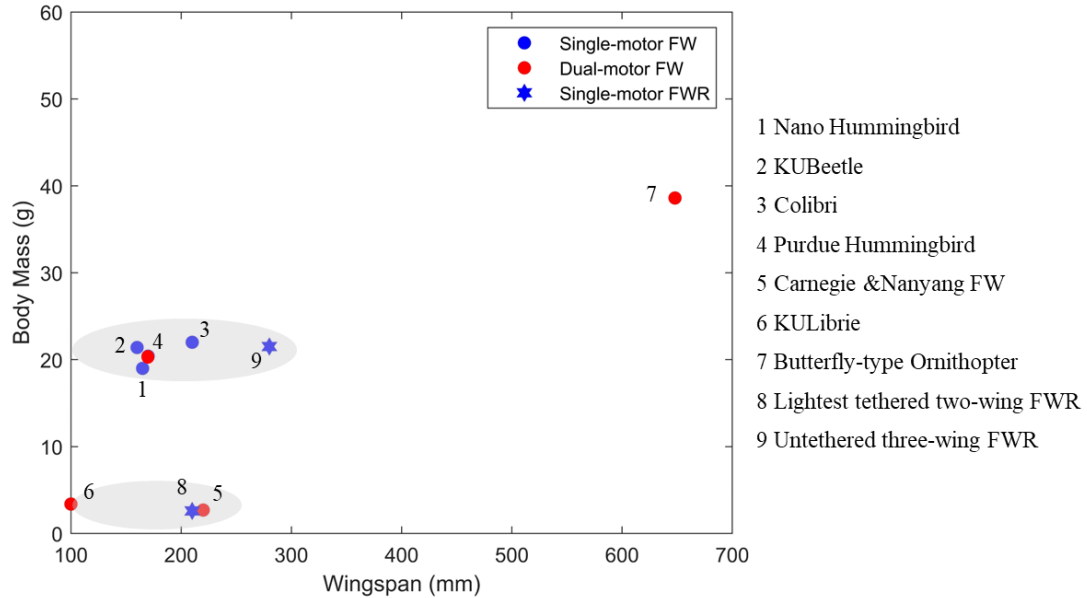


Figure 2-23 Wingspan and body mass of two-wing insect-inspired tailless FW-MAVs capable of takeoff and hovering (1 (Keennon *et al.*, 2012), 2 (Phan & Park, 2020), 3 (Roshanbin *et al.*, 2017), 4 (Tu *et al.*, 2020), 5 (Azhar *et al.*, 2013), 6 (Leys *et al.*, 2016), and 7 (Leys *et al.*, 2015)) and free-flight two-wing FWR-MAVs (8 (Guo *et al.*, 2018) and 9 (Yi *et al.*, 2017)).

2.4 Research Challenges and Development

While recent advances in bio-inspired FW-MAVs are noteworthy, practical application in complex environments remains challenging, as they cannot fully emulate genuine flying insects. Literature (Phan & Park, 2019; Helbling & Wood, 2018) proposes eight competencies essential for FW-MAVs to fulfil real-world application demands: obstacle avoidance or stable flight recovery after wing collisions, extended flight endurance, various locomotion modes (e.g., jumping, running, walking, crawling, swimming, and perching), autonomous flight, low-noise capabilities, multi-vehicle coordination, wind disturbance rejection, and low-density environment navigation. Current FW-MAVs can achieve takeoff, hovering, and maneuvering, but lack multifunctionality. Obstacles to agile flight persist in two domains: improving aerodynamic performance and overcoming

limitations in micro-scale electronics for flight controls and power supply technology.

2.4.1 Aerodynamic Performance Improvement of FWR-MAVs

Limited endurance is a prevalent issue for both FW-MAVs and FWR-MAVs due to lift production and power efficiency. Optimizing wing kinematics and geometric parameters can enhance aerodynamic performance. In particular, numerous studies have been conducted to investigate the effects of passive pitching or twist angle variation on the lift and efficiency of flapping wings and rotary wings, as well as to utilize morphing wings (Ghommam et al., 2014; Guan & Yu, 2014; Truong et al., 2013). The implementation of twisting flapping wings has been found to enhance lift by over 25% and generate a higher thrust-to-drag ratio (Guan & Yu, 2014). Wu et al. (2017) analyzed the flow structure around the wing of an FWR by the CFD method, and demonstrated that the passive wing pitching is beneficial for FWR to augment lift. Yet, current mechanical FWR models lack the capacity for pitching motion during flapping, typically featuring a fixed AoA. This limitation contributes to suboptimal aerodynamic performance in FWRs, underscoring the need for refined design strategies that enable optimized wing kinematics.

On the other hand, previous research on twistable wings for FWR has primarily focused on analyzing twisting deformation and wing-root stiffness, with earlier FWR studies employing rectangular wing planes. There is a need to explore the impacts of bio-inspired wing shapes and flexibility on FWR aerodynamic performance, seeking to offer a comprehensive understanding of aerodynamic mechanisms stemming from elastic deformation and guidelines for designing practical biologically flexible wings that yield enhanced aerodynamic benefits for FWR-MAVs.

Furthermore, as a small and light-weight vehicle, the limited output and energy capacity of portable power sources are significant challenges to its aerodynamic performance and flight capability. To address these challenges, researchers have taken inspiration from insects, which minimize flight energy using flight muscles, flight thorax, and wing hinges. Recently, elastic energy storage has been

implemented FW-MAVs, and a compliant mechanism driving the flapping mechanism at the resonant frequency has been shown to be an effective power-saving technique (Alexander & Bennet-Clark, 1977; Baek et al., 2009; Steltz et al., 2007; Tantanawat & Kota, 2007). The elastic force counteracts the inertial forces from wing motions, which in turn also influences the generation of aerodynamic forces (Baek et al., 2009). Therefore, considering the wing inertia effect and the FWR mechanical system's power efficiency, employing an elastic actuator to reduce power consumption is crucial for energy-effective flight. This will allow longer flight durations despite onboard energy limitations, due to high aerodynamic performance, efficient propulsion and power usage.

2.4.2 Flight Control and Stability System of FWR-MAVs

FWR-MAVs necessitate an active control system capable of adjusting wing kinematics during flight, resulting in the generation of control torque for attitude changes. In the three-wing FWR-MAV built by Dong et al. (2020), the attitude control mechanism incorporates stabilizers and rudders beneath the FWR driving mechanism, functioning as a tail. The attitude control mechanism incorporates stabilizers and rudders beneath the FWR driving mechanism, functioning as a tail. This model achieved relative stability and control in forward flight tests by tuning PID controller gains. However, it encountered stability issues during backward flight tests, attributed to the uneven distribution of components. A significant challenge to stability is the high vibration from flapping motions, which leads to considerable attitude overshoot, indicating a need for control algorithm enhancements.

In essence, the major obstacle for existing FWR-MAVs is the absence of a well-designed attitude control mechanism specifically tailored to their unique combination of flapping and rotary wings, along with feedback controllers for attitude and altitude regulation. Given the dynamic instability inherent in flapping mechanisms and the constraints imposed by size and weight, the design of an onboard control system capable of consistent stability and agile maneuvering remains a demanding aspect of FWR-MAV advances.

2.5 Conclusion

This review provides a comprehensive analysis of the FWR, a pioneering MAV design combining bio-inspired flapping and rotational motions, highlighting its aerodynamic efficiency. Distinct from traditional flapping wings, FWR capitalizes on swift passive rotation induced by active flapping, increasing lift and aerodynamic power coefficients. This exploration underscores FWR's unique aerodynamic mechanisms, emphasizing variations in wing kinematics and performance in both hovering and forward flight in contrast to insect flight patterns. Enlightened by these insights, lift enhancement technologies are fundamental to the research for developing efficient. In comparison to established flapping wing models, FWR showcases potential benefits in aerodynamic performance.

While progress has been made in transitioning from conceptual designs to functional models, substantial obstacles still exist. These include constraints related to weight and size, the limitations of microelectronics and power systems, intricate flight dynamics, and the lack of established control strategies. This review concludes with an in-depth discussion that identifies research gaps and focuses on overcoming the prevailing challenge of limited flight endurance. It highlights the methods to enhance the aerodynamic efficiency of FWR-MAVs, including mechanical optimization for precise wing motion and power saving and the incorporation of bio-inspired flexible wing designs. Moreover, the refinement of flight control systems emerges as another crucial challenge. Developing flight control systems for FWR-MAVs is essential for reliable stability and attitude management, enabling the full potential of FWR-MAVs in real-world applications.

Chapter 3 Aerodynamic Performance of Mechanical Flapping Wing Rotors with Passive Pitching Angle Variation

Acknowledgement: This chapter paper represents the author's original work in its entirety. It is important to note that the experiments described in Section 3.3.2 were conducted by the author using a supplementary FWR model of PPAV. This model was developed as part of a collaborative effort in which the author contributed experimentally to the following publication:

Chen, S., Wang, L., He, Y., Tong, M., Pan, Y., Ji, B. and Guo, S. (2022) 'Aerodynamic performance of a flyable flapping wing rotor with passive pitching angle variation', IEEE Transactions on Industrial Electronics, vol. 69, no. 9, pp. 9176-9184. doi: 10.1109/TIE.2021.3112964.

While references to this publication are included in this thesis and are clearly marked as citations, they are utilized solely to enhance the comprehensiveness and coherence of the discussion, underscoring the author's unique contributions within a collaborative framework.

Abstract

Earlier mechanical FWR models did not incorporate pitching during flapping, indicating a necessity to optimize FWR mechanism design for desired wing kinematics of motion. Additionally, previous studies of conventional flapping wings have mainly concentrated on passive twist from elastic deformation, noting that active pitching mechanisms are more power-intensive. In this study, two types of FWR mechanisms for passive pitching angle variation (PPAV) were designed and assessed. Employing a high-speed camera and a force measurement system, wing kinematics were captured, and lift production was measured. The initial L-shape FWR model with elastic strings (FWR Model.1 in Figure 1-2) confirmed the viability and effectiveness of PPAV. A subsequent U-shape FWR model with sleeve-pin units for PPAV (FWR Model.2 in Figure 1-2) exhibited notable enhancements in aerodynamic performance. The criticality of asymmetric stroke angles was emphasized, and the role of passive rotation in lift

generation was evaluated. This research proposed optimized mechanisms for high lift production, providing advances beyond previous FWR models.

3.1 Introduction

A study on hovering hawk moths reveals that aerodynamic and inertial forces, particularly at stroke reversal, cause passive pitching (rotation) (Zhao and Deng, 2009). Previous research on flapping wings highlights the significance of passive twisting deformation, which contributes to lift and efficiency (Guan & Yu, 2014; Truong et al., 2013). Passive deformation of the wing, such as twist and camber variation, has been found to reduce energetic costs in insect-like flapping wings during hovering (Young, 2012). Du and Sun (2008) investigated the aerodynamic effects of wing deformation in an insect-like flapping wing model, and discovered that a deformation of 6% camber and 20° twist resulted in a 10%-20% increase in lift and approximately a 10% improvement in lift-to-drag ratio compared to a rigid flat-plate wing. Similarly, Wu et al. (2017) conducted experimental measurements on flapping rotary wings and suggested that passive wing surface twist significantly enhances lift production.

However, previous studies primarily focused on elastic deformation-induced passive twist, exploring appropriate flexibility and deformation to improve aerodynamic performance, such as lift-to-drag ratio and flight efficiency of flapping wings. Furthermore, as mentioned earlier in the theoretical analysis of FWR research, FWRs with suitable angles of attack during strokes can achieve better aerodynamic performance. However, in practice, mechanical FWR models were operated with a fixed angle of attack, lacking pitching motion throughout the strokes. In addition, considering the implementation of active twist mechanisms requires additional linkage, weight, and power, investigating passive or adaptive pitching angle variation for improved aerodynamic performance becomes crucial in terms of optimizing wing motion kinematics, especially for novel FWRs.

In this study, two distinct FWR models powered by a DC motor were designed, fabricated, and tested to assess the impact of pitching angle variation on the aerodynamic performance of FWRs. This chapter begins with the exploration of an FWR model constructed by the author (FWR Model.1 in Figure 1-2), equipped

with elastic strings and an L-shape flapping mechanism to enable pitching motion, detailed in Section 3.2. The wing kinematics of motion were captured and measured using a high-speed camera, while a force measuring system was constructed to measure the total force, encompassing both inertial force and aerodynamic lift. The initial FWR model demonstrated the feasibility and effectiveness of passive pitching angle variation (PPAV). Subsequently, the author built and examined an alternative FWR model (FWR Model.2 in Figure 1-2) incorporating a sleeve-pin unit within the U-shape flapping mechanism, enabling a more compact design and variable pitching angles, as detailed in Section 3.3.1. The author conducted a set of experiments to assess PPAV's effect on FWR's aerodynamic performance by using a supplement FWR model (Chen et al., 2021) in Section 3.3.2. Furthermore, based on the compact FWR model with sleeve-pin units (FWR Model.2 in Figure 1-2), the author investigated the role of passive rotation in lift generation and underscored the importance of asymmetric stroke angles as an additional pivotal factor enhancing the aerodynamic efficiency and flight effectiveness of the current FWR models, surpassing previous studies and models, as presented in Section 3.3.3.

3.2 Experiment Study of a Flap-Pitch Mechanism for FWR

3.2.1 Wing Flapping and Pitching Motions

To accomplish the combined movement of flapping and pitching motions, the first mechanical FWR model (FWR Model.1 in Figure 1-2) was integrated with two parts as shown in Figure 3-1: a flap-pitch mechanism and an actuating device. The wing motion transmission mechanism is composed of a main spindle (1), a rotating spherical joint (2), wing twisting spars (3), L-shape actuating arms (4), cross rib bars (5) and a two-arm linkage (8), forming a four-bar mechanism that transmits both flapping and pitching motions to the wing (7). The actuating mechanism consists of a swivel bearing (9), a bearing sleeve (10), a transmission bar (11) and a drive rocker (12) connected to a DC geared motor in the motor block (13). Most FWR model components were fabricated using 3D printing, except for the wing, which was made of polyimide film (in blue) and carbon/epoxy composite rods (in black).

When the motor drives the rocker, the swivel bearing joint connected to the transmission bar causes the two-arm linkage to move vertically along the central spindle and rotate freely around it. The pair of wings, installed anti-symmetrically around the central axis, are actuated to generate lift and thrust, revolving around the center due to their inverse self-propulsion.

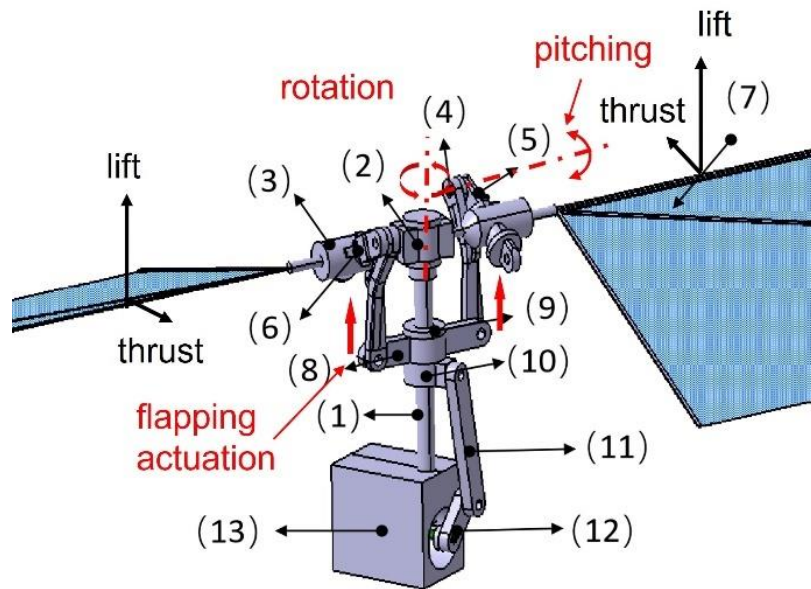


Figure 3-1 Initial structural diagram of flap-pitch FWR mechanical model.

The wing flap-pitch mechanism is designed to symmetrically flap up and down by 45° , with the wing twisting between -5° and 25° about the leading edge where the wing spar is located. Positive flapping angles occur when the wing moves upward vertically across the horizontal plane, and positive pitching angles occur when the wing pitches up.

To briefly describe the mechanism kinematics, assume the wing initiates an upward stroke with flapping and pitching angles at -45° and -5° , respectively, as shown in Figure 3-2. As the L-shape actuating arms move upward, the peak where the L-shape arm and the cross-rib bar are hinged together rises from position 1 to 2, causing the crossbar to twist around the hinge point, limited to 25° . With the peak of the L-shape arm rising from position 2 to 3, the arm and the cross rib collectively push the wing spar to twist and move up, enabling the wing

to beat upward with a pitching angle of 25° . The flapping angle reaches a maximum of 45° at the end of the upstroke (position 3).

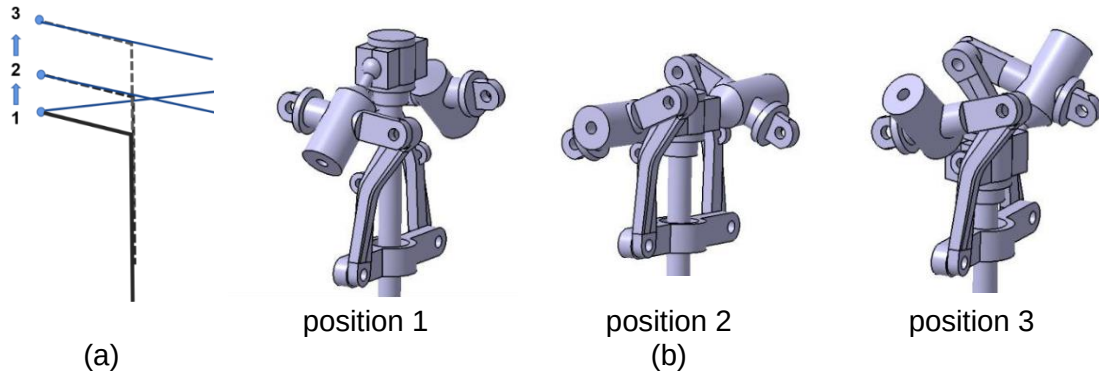


Figure 3-2 (a) Upstroke movement diagram of L-shape actuating arm and cross rib bar; (b) Corresponding positions 1 to 3.

Position 3 marks the end of the upstroke and the beginning of the downstroke. As the peak descends from position 3 to 4, the L-shape actuating arm initiates pulling the cross-rib bar to twist down, as illustrated in Figure 3-3. The tailing point of the crossbar is connected to a buckle on the L-shape arm by a string, limiting the cross-rib bar rotation to -5° . Subsequently, the wing completes the downward flapping to its maximum angle of -45° at position 1, facilitated by the pulling force generated by the L-shape arm, cross-rib bar, and string. Consequently, position 1 also signifies the end of the downstroke. During the downstroke, the wing is subjected to high loads. Connected by the elastic string, this results in passive and adaptive pitching rotation about the peak of the L-shape arm due to the combined effects of aerodynamic, inertial and elastic forces.

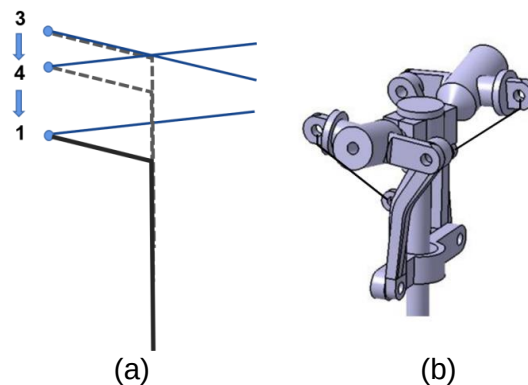


Figure 3-3 (a) Downstroke movement diagram and (b) the corresponding position 4.

As depicted in Figure 3-4, the FWR's strokes can be expressed as:

$$S_{flap} = a(\sin(|\phi_{u_{max}}|) + \sin(|\phi_{d_{max}}|)) \quad (3-1)$$

$$S_{twist} = b(\tan(|\alpha_{u_{max}}|) + \sin(|\alpha_{d_{max}}|)) \quad (3-2)$$

$$S_{total} = S_{flap} + S_{twist} \quad (3-3)$$

where S_{flap} and S_{twist} represent the time-varying flapping and twisting (pitching) strokes, respectively; 'a' is the distance between the flapping center and the twisting center on the wing twisting spar; 'b' is the distance between the peak of the L-shape arm and the twisting center on the cross-rib bar. The total driving stroke can be calculated as the sum of flapping and twisting strokes. Consequently, reducing the lengths of 'a' and 'b' on the L-shape arm and cross-rib bar is efficient for minimizing the driving travel of the actuation mechanism, ultimately requiring less power.

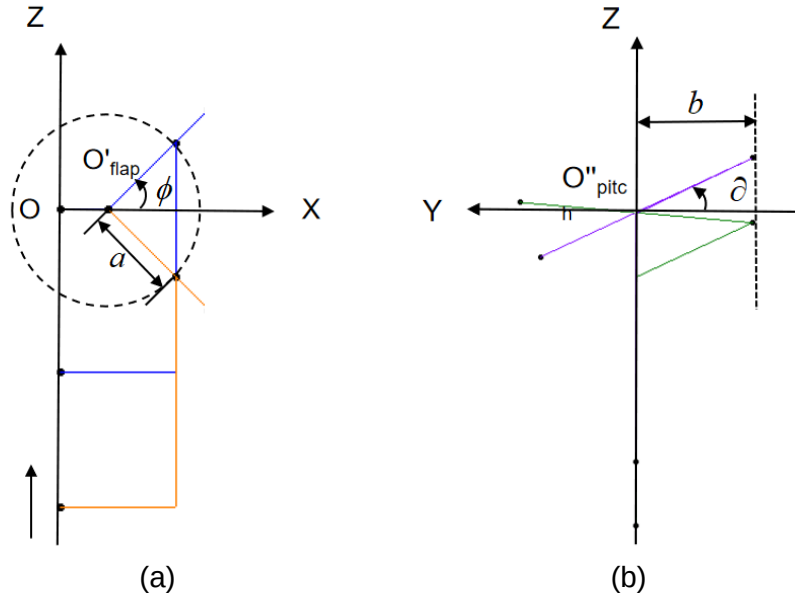


Figure 3-4 (a) Coordinate diagrams of the wing flapping motion and (b) pitching motion: the Z -axis represents the main axis of the model; the coordinate origin O is the spindle core; the ' O'_{flap} ' is the flapping centre; the ' O''_{pitch} ' is the pitching centre.

3.2.2 Flap-Pitch FWR Test Model and Experiment Setup

The FWR test model, as shown in Figure 3-5, validates the proposed wing flap-pitch mechanism. Key structural components are 3D printed from compound

nylon material. The initial spherical joint design is replaced by a metal ball link for greater flapping amplitudes. The main spindle and bearing use hollow stainless steel to minimize weight, and joints are secured with carbon rods, pins, or screws and nuts. The wing is made of 15 μm polyimide resin skin and carbon rods, with a total model weight of 22.59 g.

The experimental setup for FWR model measurements includes a load cell (200 g capacity, 0.05% F.S accuracy) to measure instantaneous dynamic force in the transverse direction. The load cell converts force into voltage, which is amplified (1k gain) and transferred to a PC-connected signal acquisition card (NI USB-6009). Signals are monitored and processed using LabVIEW software, with data filtered by a 2nd order low-pass Chebyshev filter. The low-pass cut-off frequency is set at five times the FWR model's flapping frequency.

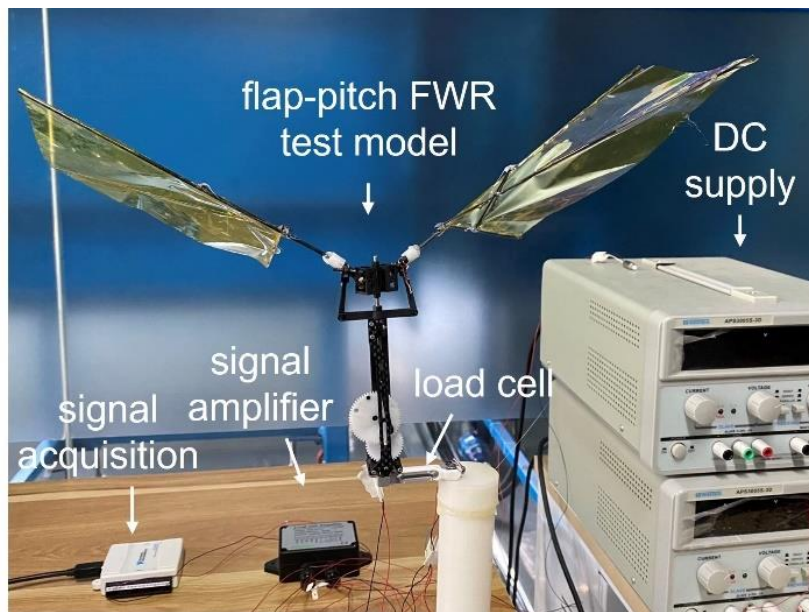


Figure 3-5 Flap-pitch FWR test model and load cell measurement system.

3.2.3 Kinematic and Force Measurement Results and Discussion

3.2.3.1 Effect of Elastic Strings on Wing Kinematics of Motion

In Figure 3-6(a), the model is positioned in front of the high-speed camera, with its vertical plane parallel to the field of view, allowing direct measurement of wing positions from each camera frame, using the two perpendicular reference lines in

the field. It was observed that the actual wing motion kinematics are amplified due to the elastic strings.

As shown in Figure 3-6(b)(c), the flapping angle varies between -41.67° and 48.76° , and the pitching angle ranges from -24.33° to 54.27° , which is considerably higher than the defined pitching angle variation of the mechanism with a pitching amplitude of 30° (ranging from -5° to 25°). Analysis of collected frames from a flapping cycle reveals rapid wing twisting at stroke reversals, like insect flapping flight, with supination occurring at the end of the downstroke and pronation at the end of the upstroke, as shown in Figure 3-6(d)(e). In this test, the FWR model generated a total force of 8.8 g, with flapping and rotation frequencies of 5.5 Hz and 2.3 Hz, respectively.

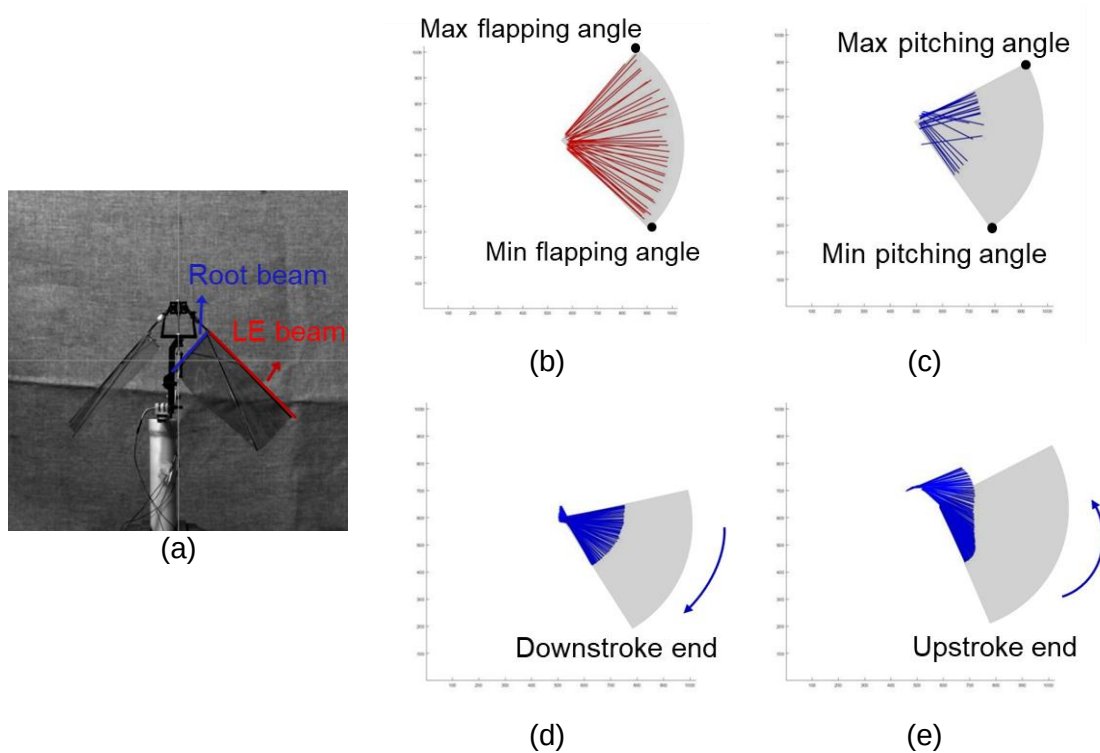


Figure 3-6 (a) High-speed camera view; Captures of (b) flapping and (c) pitching motion; Rapid twist at the end of (d) downstroke and (e) upstroke (red line represents the wing's leading-edge beam; blue line represents the wing root beam).

3.2.3.2 Optimal Kinematics of Flap-Pitch FWR

Compared to the previously discussed wing motions, the flapping mechanism in this case was adjusted to have a smaller flapping amplitude of 70° and

significantly asymmetric angles at the maximum and minimum stroke, ranging from -30° to 40° . Camera recordings show the passive pitching angle variation during flapping cycles from approximately -7° to 40° . As showed in Figure 3-7, with an input voltage of 4V, the flapping frequency reached 7 Hz, generating an average total force of 15.95 g. The maximum positive and negative forces are 45.81 g and -20.14 g, respectively. Upon increasing the input voltage to 5 V, the flapping frequency rose to 9.25 Hz, producing an average total force of 24.12 g, with a considerable reduction in negative lift. Consequently, this FWR model successfully generated sufficient vertical force to overcome its weight, demonstrating its potential capabilities for take-off and hovering. Furthermore, compared to the previous wing motions in the above subsection, the flapping and rotation frequencies increased significantly. These results suggest that adopting a smaller negative pitching angle is beneficial, as a small angle of attack at mid-downstroke improves lift and thrust generation.

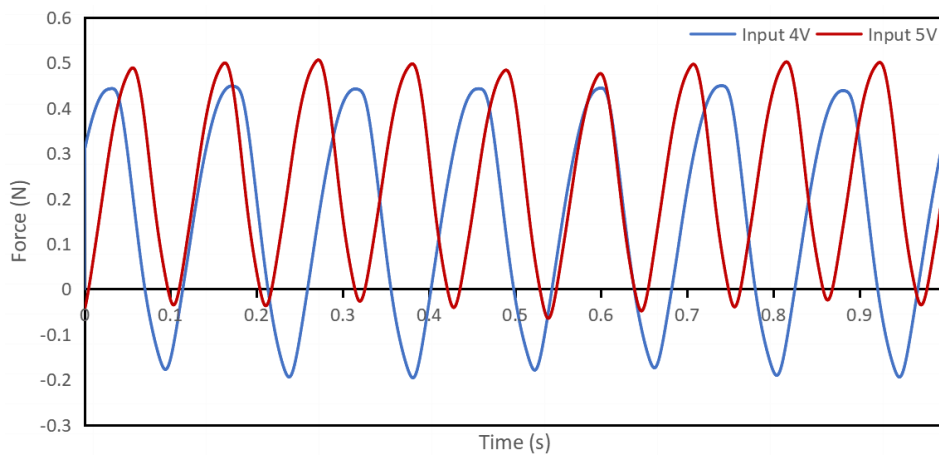


Figure 3-7 Instantaneous force of the FWR test model with 4 V and 5 V input voltage.

3.3 Analysis and Experiment of FWRs with PPAV

3.3.1 Optimal Flap-Pitch Mechanism Concept for FWR with PPAV

The FWR Model.2 has been optimized from Model.1, with a focus on a more compact mechanical design suitable for manufacturing. This optimization includes a novel sleeve-pin unit, installed at the end of one side of a U-shaped flapping mechanism, as shown in Figure 3-8. This new unit serves as a replacement for the elastic string and L-shaped flapping mechanism used in FWR

Model.1. By inserting the wing spar root into the sleeve, the wing is allowed to rotate freely around the wing spar axis (z_w axis), but its motion is constrained by an 'angle limiter' stopper integrated into the sleeve, limiting the pitching amplitude to 40° . During the flapping motion, the wing's pitching motion consists of both rigid free pitching and elastic deformation twist, which are passively induced by aerodynamic and inertial forces acting on the wing.

The flapping, pitching, and rotation angles are denoted by ϕ , α , and ψ , respectively. As per the high-speed camera observations from Section 3.2.3, the wing kinematics of motion for an FWR model of PPAV are depicted in Figure 3-9. For instance, at the beginning of the upstroke, the wing passively and rapidly pitches up to the maximum limit of $\alpha_1 = 30^\circ$ then maintains this angle throughout the remainder of the upstroke. During the downstroke, the wing rotates in the opposite direction, reaching a minimum pitching angle of $\alpha_2 = -10^\circ$.

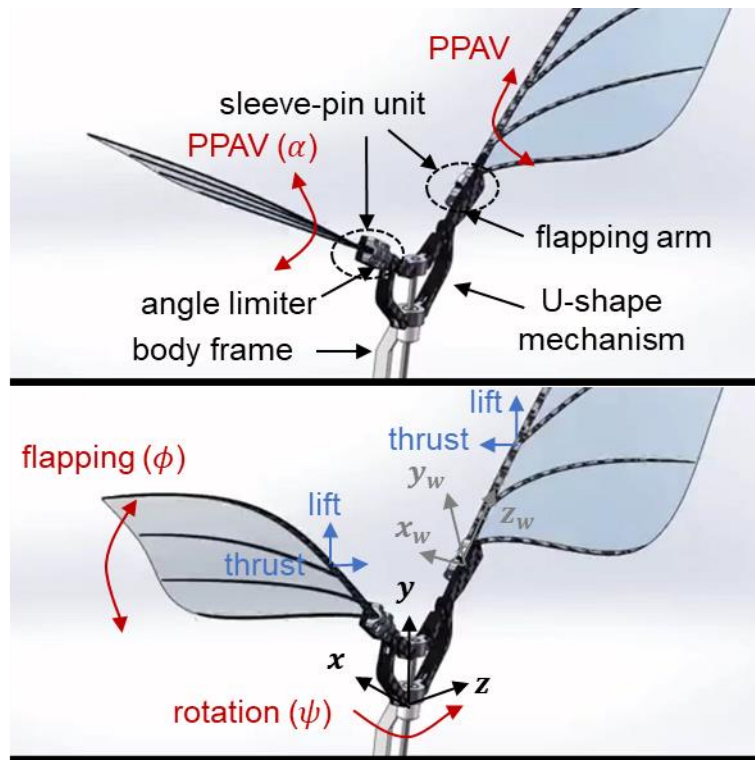


Figure 3-8 The U-shape FWR model with sleeve-pin unit for PPAV

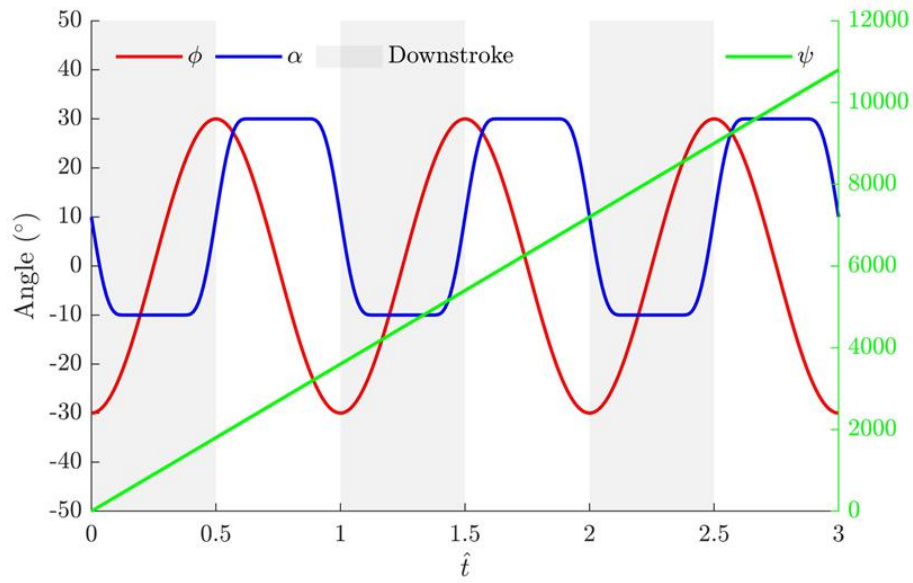


Figure 3-9 Wing kinematics of motion of the FWR model with PPAV.

3.3.2 Effect of PPAV on the FWR Aerodynamic Performance

This study, which investigates the optimal flap-pitch FWR mechanism (FWR Model.2), initially focused on examining the impact of PPAV on the aerodynamic performance of an FWR model, as shown in Figure 3-10. The tested mechanical FWR model has been manufactured as detailed in the published paper (Chen et al., 2021).

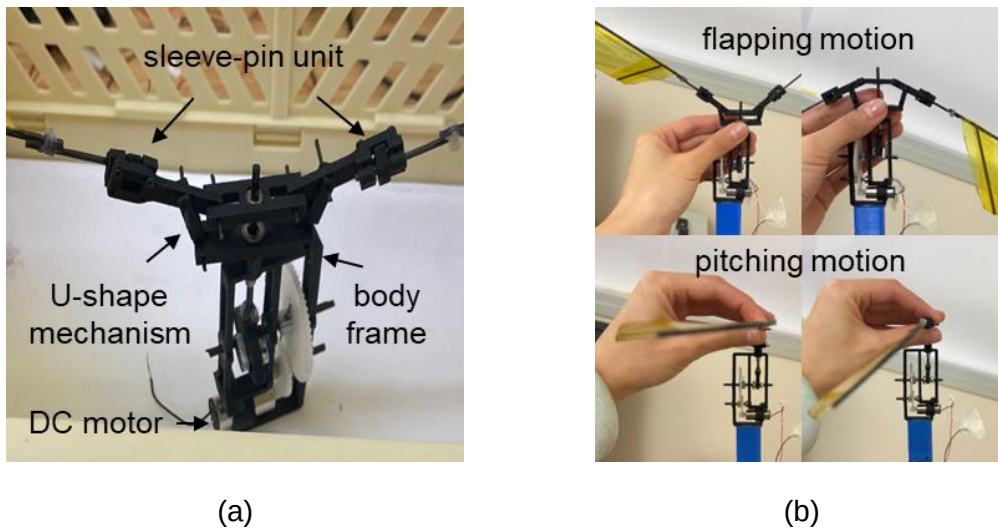
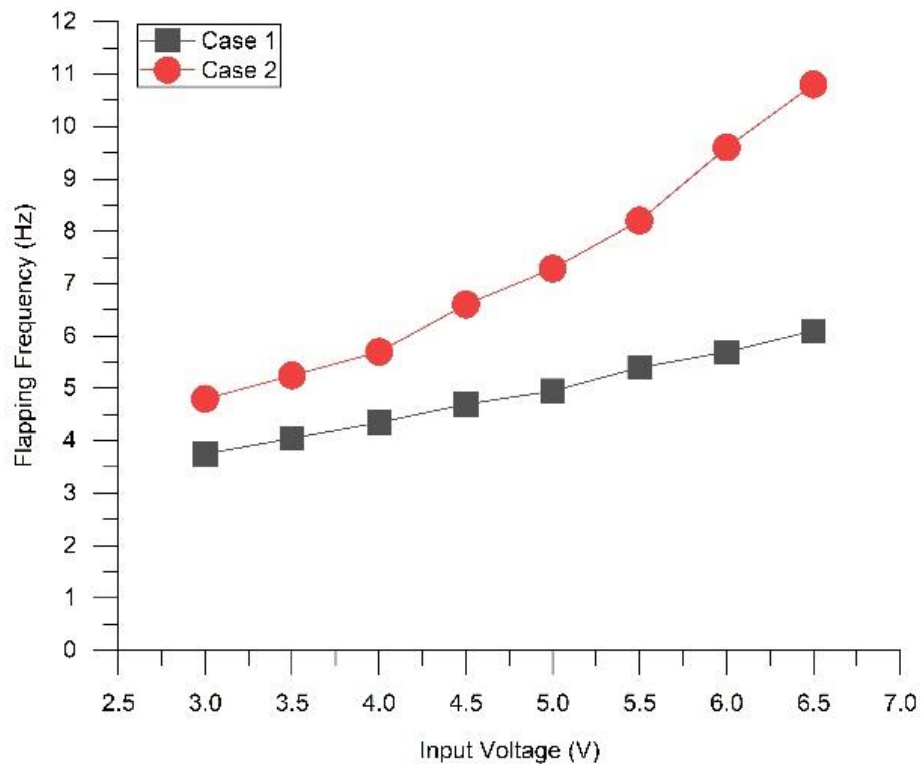


Figure 3-10 (a) The tested FWR model of PPAV and (b) its flapping and pitching angle variations.

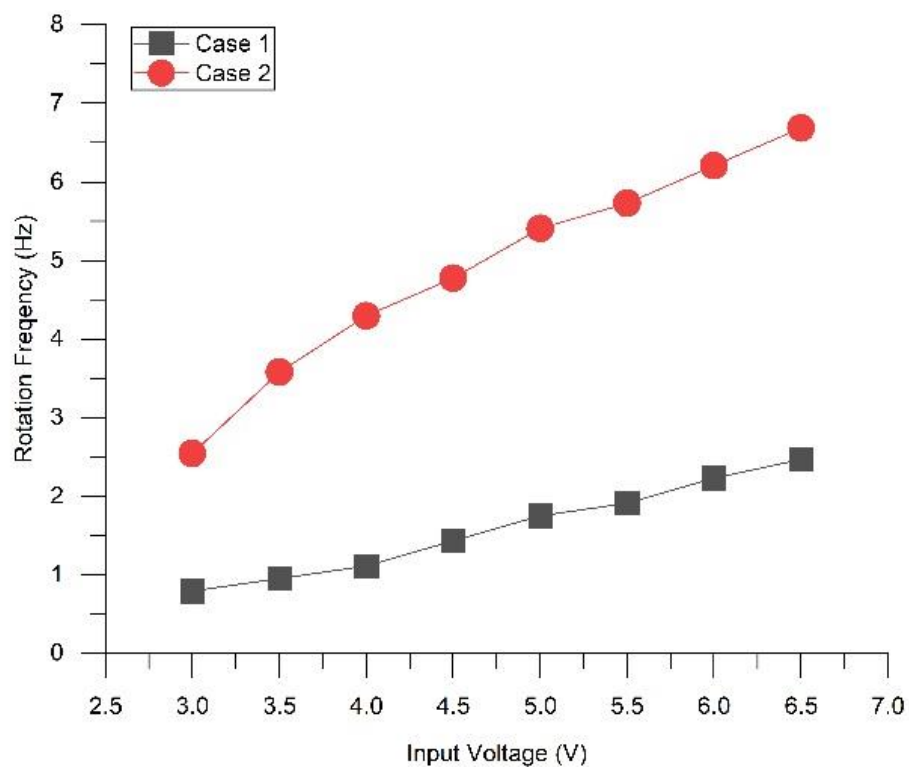
In experiments, the FWR featured a rectangular, membraned wing with a 145 mm span, a 90 mm chord, and a 1.5 mm diameter leading-edge rod. The U-shaped flapping mechanism was actuated by a DC motor which featured 15 W power rating, 7.4 V voltage rating, and operated at 30,000 rpm, to conduct the flapping motion with maximum $\phi = 50^\circ$ and minimum $\phi = -20^\circ$ stroke angles below and above the horizontal plane, respectively. Two experimental scenarios were designed to analyse the FWR's aerodynamics with PPAV. Case 1 employed a constant 30° pitching angle, while Case 2 featured a 10° to 50° pitching angle variation. Using the experimental setup depicted in Figure 3-5, measurements of flapping and rotation frequencies, along with lift and lift-to-power ratios, are presented in Figure 3-11.

Figure 3-11(a)(b) shows that the flapping and rotation frequencies increased linearly with input voltage, with Case 2 exhibiting higher frequencies than Case 1. The lift-voltage relationship was nearly linear, and Case 2 produced approximately twice the lift of Case 1, as seen in Figure 3-11(c). In Figure 3-11(d), the lift-to-power ratio represents the FWR aerodynamic efficiency. While Case 1's ratio increased with input voltage, Case 2's ratio decreased significantly but remained substantially higher due to greater lift production and rapid rotation speed.

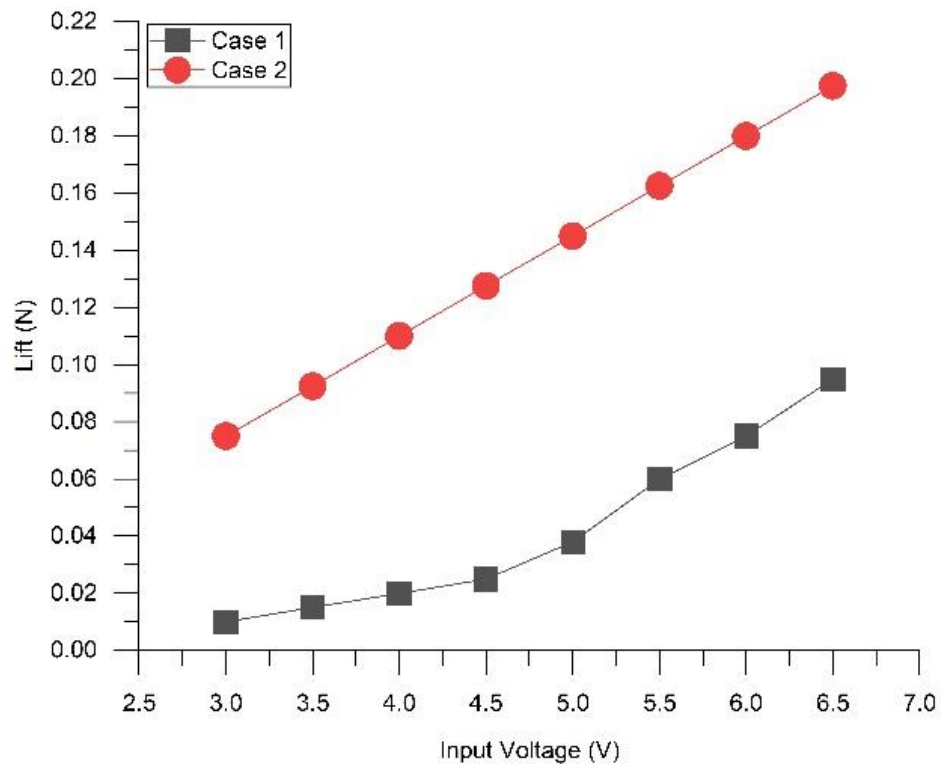
The results also demonstrated that the maximum average lift force in Case 2 was 20.15 g, exceeding the FWR model's net weight (18.7 g). The paper (Chen et al., 2021) ultimately demonstrated that this model achieved successful takeoff and free flight, carrying a 4 g cable when the input voltage was raised to 9 V. This outcome emphasized the effectiveness of the sleeve-pin unit in realizing passive pitching motion, leading to a significant increase in aerodynamic lift and performance compared to an FWR with a constant pitching angle.



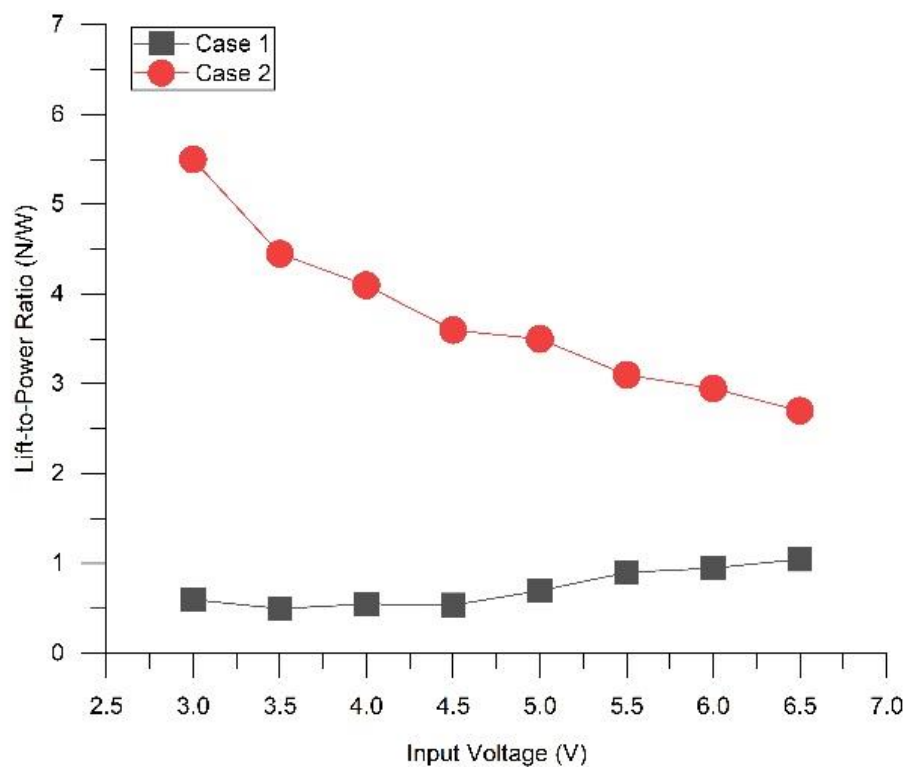
(a)



(b)



(c)



(d)

Figure 3-11 Test results of the FWR with PPAV in a range of input voltage: (a) flapping frequency, (b) rotation frequency, (c) average lift over a flapping cycle, and (d) lift-to-power ratio

3.3.3 Effects of Rotation Motion and Asymmetric Flapping Motion for Lift Enhancement of FWR with PPAV

Furthermore, in alignment with the optimal concept, the well-refined FWR model with PPAV (FWR Model.2) was manufactured, as shown in Figure 3-12. This compact model was effectively used to investigate the impact of wing kinematics of motion including rotation and asymmetric flapping motion on the FWR aerodynamic performance.

3.3.3.1 Rotation Motion

In Case 1, this model featured symmetrical flapping motion with a stroke angle range of -40° to 40° and a pitching angle variation of 0° to 35° . The influence of self-propelled rotation, a key characteristic of FWR, was examined by comparing the FWR model to a benchmark case of FWR without rotation.

Figure 3-13(a) shows that as the input voltage increased, the flapping frequency of the FWR gradually surpassed that of the non-rotating case. As a result, the lift production was improved for the FWR model, as depicted in Figure 3-13(b). For example, the rotation motion contributed to approximately 30% of lift generation under a constant power input of 3.5 V. Figure 3-13(c) reveals that when the flapping frequency was 8.16 Hz, the average lift generated by the model over a flapping cycle was 11.52 g and 10.48 g for the FWR mode under 3.5 V and non-rotating case under 4 V, respectively. The above results indicate that the average lift generated by the FWR approximately remained consistent at the same flapping frequency. Thus, the rotation motion primarily contributed to reducing power consumption since the power input for the FWR was lower than that of the non-rotation case. Overall, rotation motion plays a significant role in increasing lift and saving power, thereby achieving great aerodynamic efficiency.

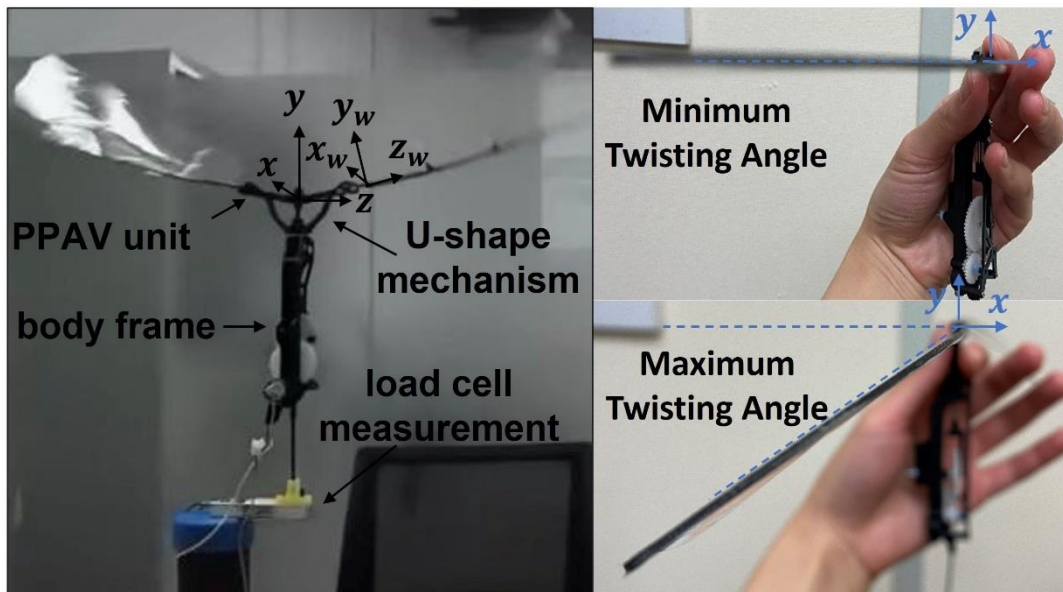
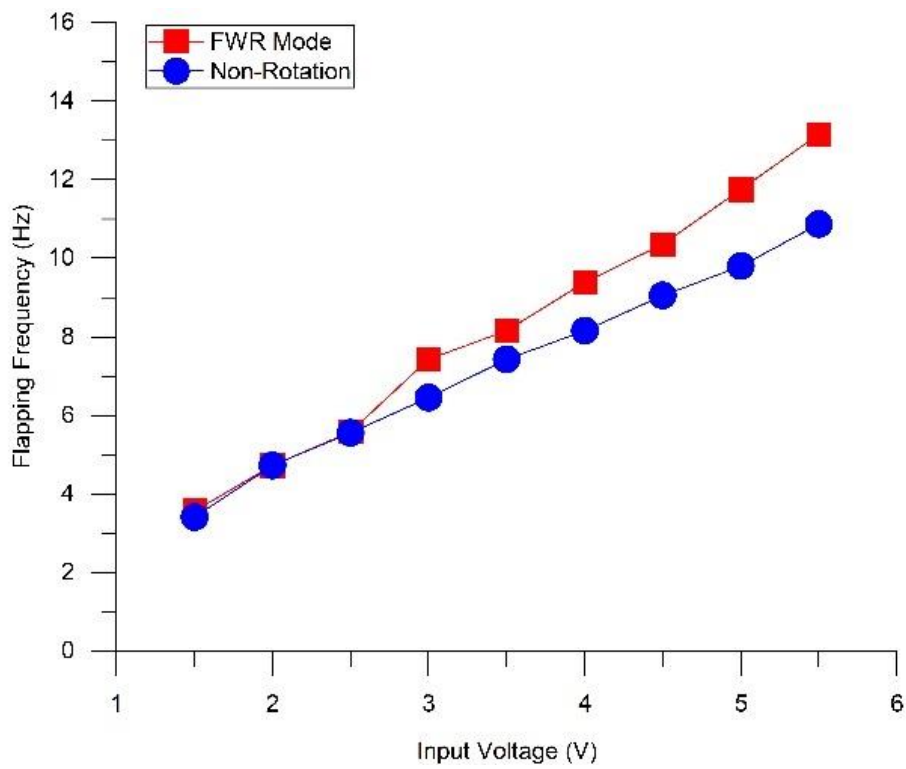
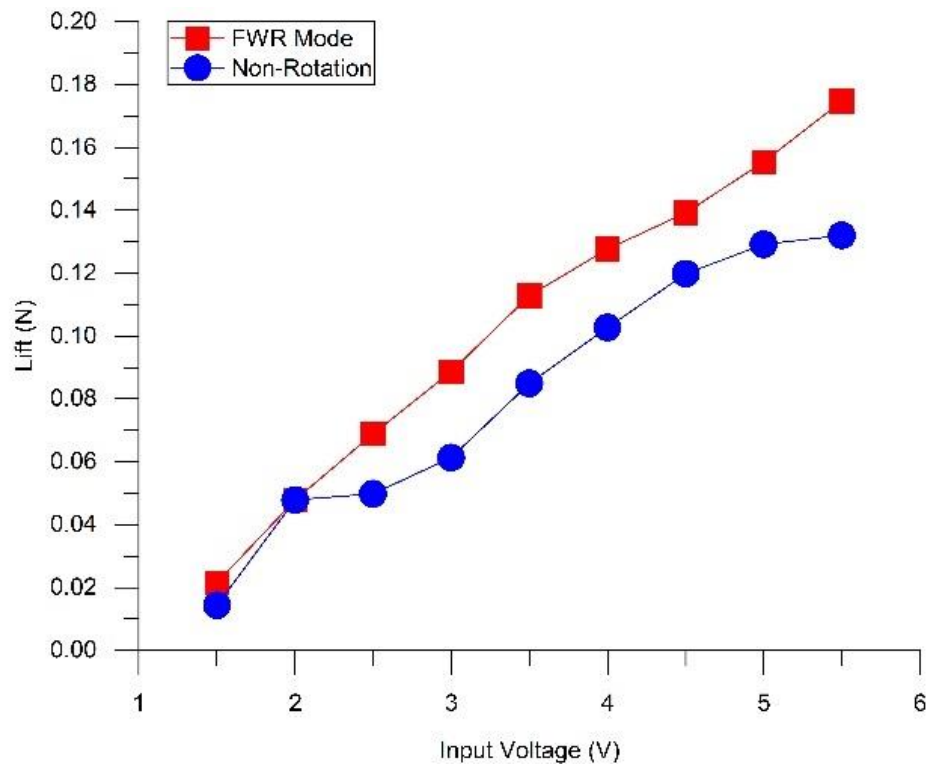


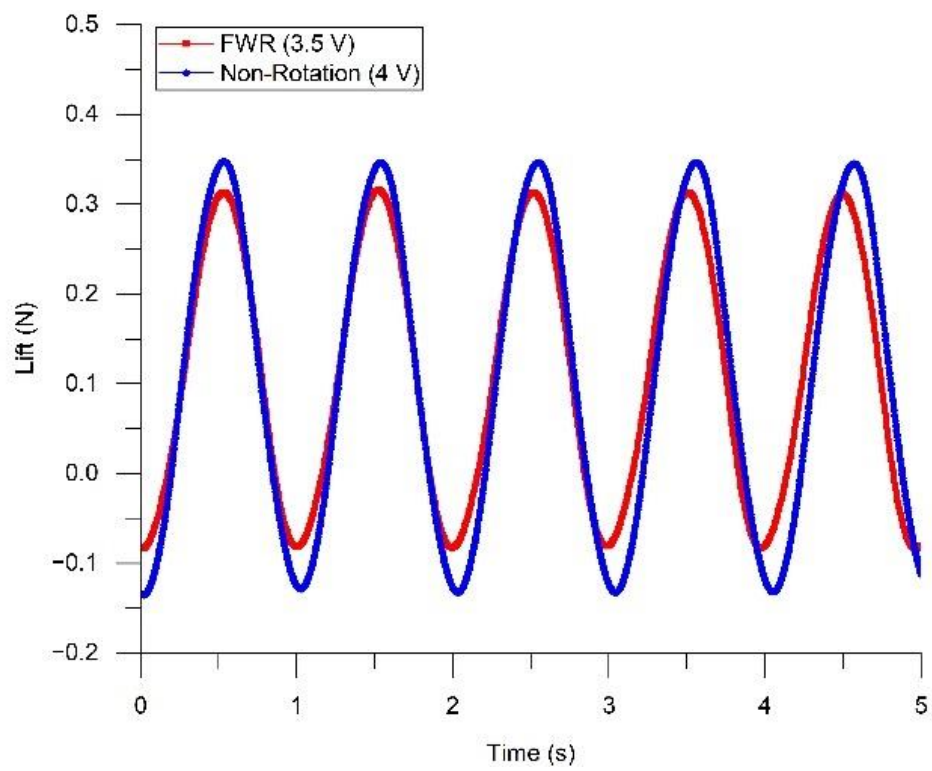
Figure 3-12 FWR model with a passive pitching angle variation from 0° to 35° .



(a)



(b)



(c)

Figure 3-13 Variation of (a) flapping frequency and (b) average lift over a flapping cycle with input voltage; (c) Comparison of FWR model and non-rotation FWR case at the same flapping frequency of 8.16 Hz.

3.3.3.2 Asymmetric Flapping Motion

All previous studies on FWR have utilized symmetrical flapping motions where the maximum and minimum stroke angles are identical. However, as discussed in Section 3.2.3.2, the initial FWR model (FWR Model.1), which utilized an L-shaped mechanism for asymmetrical flapping motion with a stroke angle range of -30° to 40° , was successful in achieving high lift production.

In Case 2, the current model (FWR Model.2) retains the asymmetrical flapping motion with stroke amplitudes of -30° and 40° , while it also executes a pitching angle variation from 7° to 42° . This maintains a consistent pitching amplitude with Case 1, where the flapping motion is symmetrical with a stroke amplitude of 40° . The force measurement results for Case 1 and Case 2 are compared in Figure 3-14. This comparison indicates that adopting an asymmetrical flapping motion significantly enhances lift production, which is crucial for overcoming the vehicle's weight and serves as a key factor in enabling the FWR model's flights. This practical application marks a significant progression and deviation from earlier FWRs, which primarily relied on symmetric flapping motions and faced challenges in achieving effective flight.

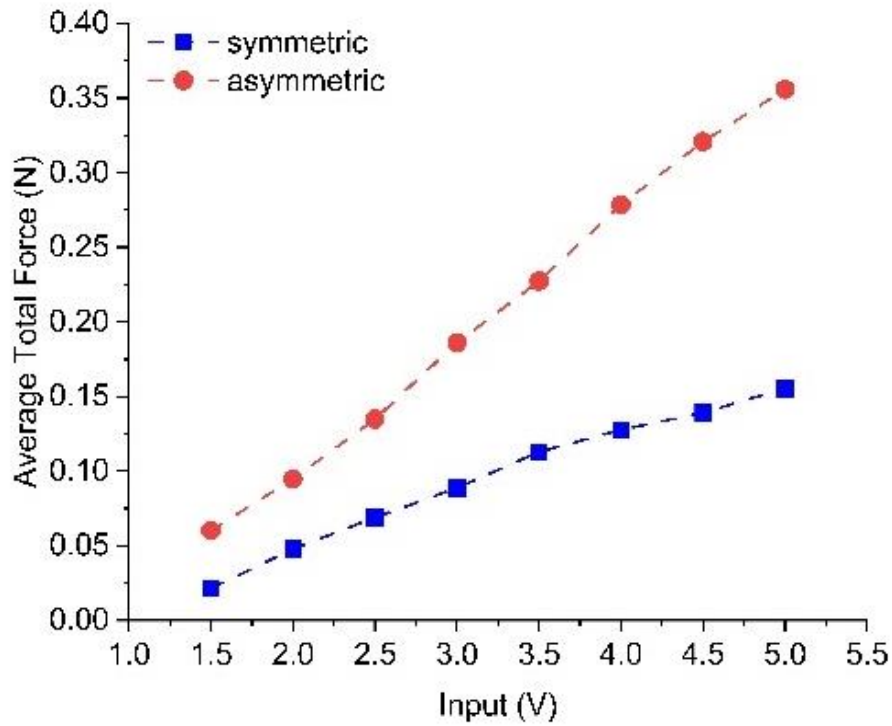


Figure 3-14 Average total force of the FWR model over a flapping cycle in a range of input voltage.

3.4 Conclusion

In this study, two types of mechanical models (FWR Model.1 and FWR Model.2 in Figure 1-2) were proposed for FWR-MAVs to truly achieve a combination of flapping and pitching motions. This advances the development of FWR-MAVs, which previously only executed flapping motion with a fixed angle of attack. The first model (FWR Model.1), featuring L-shaped beams and elastic strings, demonstrated the mechanical feasibility of pitching angle variation. A high-speed camera was utilized to examine wing motions, revealing rapid pitching angle variation during stroke reversal periods. By optimizing the wing kinematics of motion with a small negative pitching angle limitation, this model achieved high flapping and rotation frequencies, significantly reducing the negative lift generated during the upstroke. As a result, it produced sufficient lift to overcome the vehicle's weight.

The second model (FWR Model.2) was optimized by incorporating a novel sleeve-pin unit on the U-shape flapping mechanism. This feature allows for PPAV

in response to aerodynamic and inertial forces generated during flapping. The effectiveness of PPAV in enhancing FWR aerodynamic performance was validated by designing, manufacturing, conducting experiments, and analysing the test models with different wing kinematics of motion. The following conclusions were made:

- Experiments of the supplement FWR model revealed that PPAV improves lift production by increasing flapping and rotation frequencies. It generated twice the average lift over a flapping cycle when the pitching angle ranged from 10° to 50° , compared to the baseline model, which had a constant 30° pitching angle, under the same input.
- Rotation motion, a key characteristic of FWRs, contributed to 30% of lift production for the FWR model (FWR Model.2) which had a pitching angle variation ranging from 0° between 35° . Rotation motion allowed the FWR to save power at a given flapping frequency, compared to the benchmark case without rotation.
- Asymmetric flapping motion, with a flapping amplitude ranging from -30° to 40° , enabled the FWR model (FWR Model.2) to produce twice the force compared to the same model with symmetric stroke amplitudes of 40° , under the same input. Different from previous study, this becomes a critical factor for increasing the lift production of an FWR with PPAV.
- The compact mechanical design (FWR Model.2) offered a straightforward, easily manufactured, and operationally efficient solution for attaining the predefined flapping and pitching motions in an FWR mechanism, compared to the initial flap-pitch model (FWR Model.1). This model serves as the basis for subsequent investigations (Chapter 4 and 5) aimed at further optimization and enhancement of aerodynamic efficiency.

Chapter 4 Analysis and Experiment of an Efficient Elastic Mechanism for Flapping Wing Rotor

Acknowledgement: In this chapter paper, the author's colleague, Xun Huang, was responsible for conducting the take-off flight of the FWR model, as shown in Figure 4-13 in Section 4.3.4.

Abstract

Flapping-wing rotor (FWR) is a novel micro aerial vehicle configuration, featuring unique wing motion kinematics that combine active flapping and passive rotation for high lift production. Power efficiency in flight has recently emerged as a critical factor in FWR development. This study investigates an elastic flapping mechanism to enhance FWR power efficiency by incorporating a spring into the system. The elastic force counteracts the system's inertia for accelerating or decelerating the wing motion, reducing power demand, and increasing efficiency. Numerical analytical and experimental models of FWR were developed to simulate and measure FWR kinematics and resulting forces, focusing on the impact of spring stiffness on aerodynamic performance and power efficiency. Using optimal spring stiffness near the mechanical system's resonance, the results showed a 16% increase in power efficiency compared to the baseline model without a spring, with both models generating equal average lift force. Finally, the FWR model achieved vertical take-off in flight tests, weighing a total of 27.79 g with onboard power and a control receiver. In comparison to the first 2.6 g flyable FWR prototype from 2017, the current model produces 10 times greater lift force and has a nearly doubled wing area.

Keywords: elastic mechanism, flapping-wing rotor, micro aerial vehicle, power efficiency, power reduction.

4.1 Introduction

Flapping-wing micro aerial vehicles (FW-MAVs), which mimic insect flight characterized by remarkable manoeuvrability, agility, and hovering capability, exemplify a sophisticated example of mechanizing miniature-scale flying systems

using unsteady aerodynamics (Lentink, 2013; Roberts et al., 2016). However, FW-MAVs inherently face challenges in manufacturing and efficiency, particularly due to limited onboard energy storage for adequate flight endurance. Reduced aerodynamic efficiency at low Reynolds numbers and limited energy capacity hinder FW-MAVs from achieving long-loiter or hovering times exceeding 60 min (Pines & Bohorquez, 2006; Keennon et al., 2012; Phan & Park, 2019, 2020; Roshanbin et al., 2017; Tu et al., 2020; Coleman & Benedict, 2015; Karasek et al., 2018; Nguyen & Chan, 2019). For example, the 28.2 g Delfly Nimble developed by Karásek et al. (2018) despite being a significant advancement, only hovers for 5 min. Furthermore, increasing the power supply has not substantially improved FW-MAVs' endurance, because their mechanisms are energetically expensive (Ellington, 1984a). A 20.4 g hummingbird robot, which employed a dual-motor system, only flew for 20 s before losing control (Tu et al., 2020). In comparison, the 19 g Nano Hummingbird, with a single motor and similar wingspan and weight, achieves a maximum flight endurance of 4 min (Keennon et al., 2012). Apart from the high energy cost of the flapping mechanism, the intrinsic low aerodynamic efficiency of flapping wings also contributes to the issue.

To enhance lift and power efficiency, researchers have made efforts to develop novel flapping-wing rotor (FWR) MAVs in recent years. Studies indicate that FWRs, incorporating active flapping and passive rotation, yield considerable enhancements in aerodynamic performance compared to conventional insect-like flapping wings (Li et al., 2011; Guo et al., 2018). Theoretical analyses suggest that FWRs can generate more than double the lift of rotary wings at equivalent power efficiency levels (Li et al., 2017). Dong et al. (2020) achieved free flight with a 30 g, three-winged FWR, but it failed to maintain sustained flight due to controllability and power constraints. Chen et al. (2021) developed a 22.7 g, two-winged FWR with passive pitching, achieving vertical take-off and free flight. Research also indicates that passive wing pitching effectively achieves nearly optimal kinematics of flapping motion and enhances aerodynamic efficiency (Guan & Yu, 2014; Truong et al., 2013). Consequently, the FWR with passive pitching exhibits higher aerodynamic efficiency than Dong's three-winged model

(Dong *et al.*, 2020). However, Chen's model necessitated a 9 V input from a ground-based DC source for flight tests, instead of utilizing an onboard battery. Given recent advances in onboard-powered FWR flight, concerns regarding FWR power efficiency are increasing, with effective power utilization by the FWR mechanism becoming a critical factor.

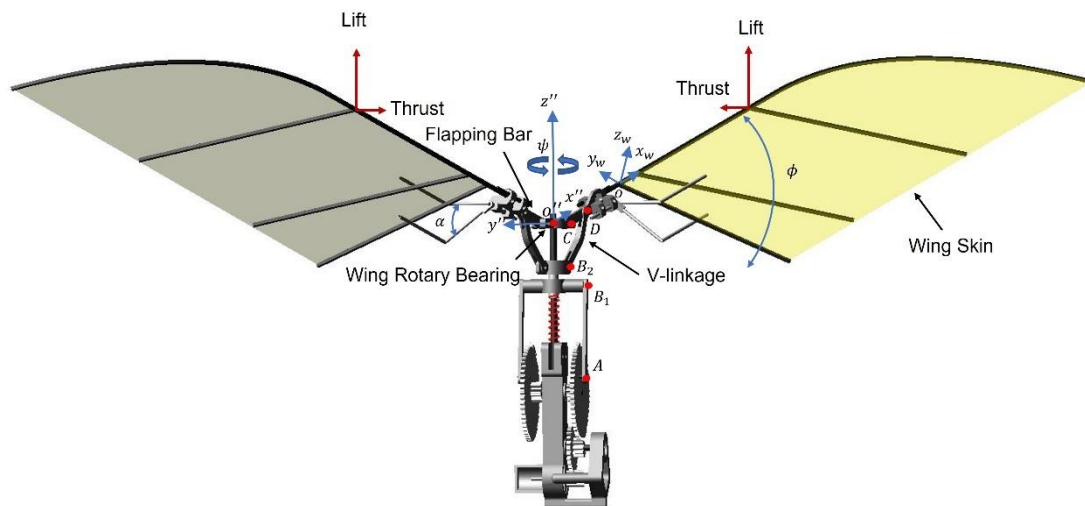
Insects utilize elastic storage, such as their flight muscles, thorax and wing hinges, to minimize flight energy consumption (Alexander & Bennet-Clark, 1977; Ellington, 1985). This is achieved by eliminating the inertial cost of wing acceleration through energy storage during wing deceleration in the previous stroke, resulting in the total mechanical power required for insect flight being solely for aerodynamic forces (Zhao & Deng, 2009). Previous studies on conventional FW-MAVs have identified two strategies for mimicking such elastic storage: implementing an entirely elastic flapping mechanism (Lau *et al.*, 2014) or introducing an elastic component in a motor-driven rigid body mechanism (Steltz *et al.*, 2007; Wood, 2007; Madangopal *et al.*, 2005; Tantanawat & Kota, 2007).

This study explores the potential benefits of incorporating elastic energy storage in FWRs. While Beak *et al.* (2009) demonstrated an efficient resonant drive for a motor-driven slider-crank flapping-wing robot coupled with a spring, achieving a 19% power reduction at 16 Hz compared to a spring-less system flapping at the same frequency in air, the application of springs in FWRs remains relatively unexplored. FWRs, featuring asymmetrically installed wings, undergo passive rotation around the central body axis during flapping, which enhances lift and reduces required power input, setting them apart from conventional FW-MAVs. The study investigates the impact of the elastic mechanism on the coupled motions and unsteady aerodynamic performance of FWRs and assesses the potential power savings, both of which are essential for advancing FWR-MAV design and have not been thoroughly examined in the context of FWRs. By focusing on the unique aspects of FWRs and the underexplored area of spring implementation to enhance FWR flight capabilities, this study underscores its importance and contributions to the field.

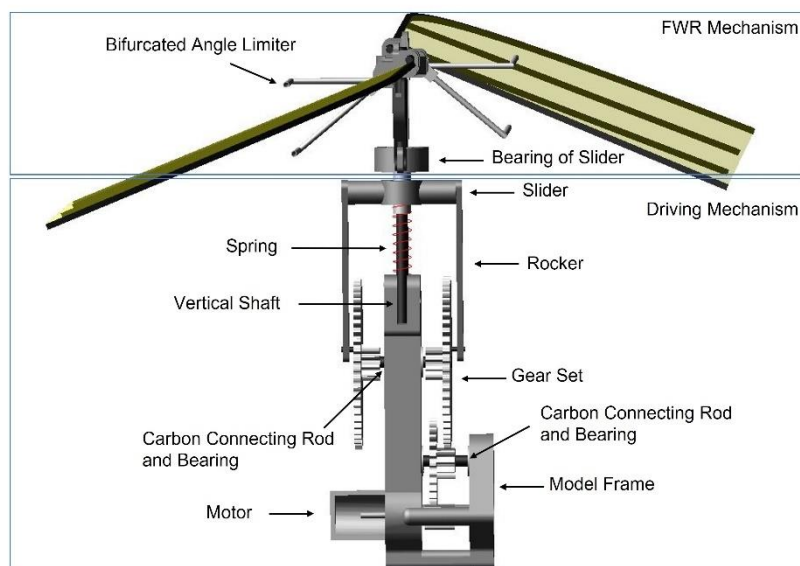
In this paper, we first develop a nonlinear dynamic model of the FWR mechanism, combined with unsteady aerodynamic model of the FWR wing, to analyse the system's dynamic behaviour. A constant motor speed with the required torque determined the mechanical system's resonance, while the effects of spring stiffness on the kinematics of FWR motion and aerodynamic and inertial forces were examined. Subsequently, an FWR test model was constructed, and total force measurements were taken from experiments. By comparing force production in the FWR model with varying springs against input power at different motor speeds (flapping frequencies), the relationship between spring stiffness and power efficiency was established. Ultimately, the FWR model was rebuilt to incorporate an onboard power unit and control device, successfully achieving vertical take-off flight.

4.2 The Spring-integrated Flapping Wing Rotor and Analysis Method

The FWR model, as illustrated in Figure 4-1, is driven by a 3.7 V DC motor operating at 4000 rpm and incorporates a 19.5:1 double reduction gear unit. Component masses are detailed in Table 4-1. A pair of wings with a spanwise length of 330 mm, mounted on a vertical shaft via a V-shaped linkage, are arranged in an axially symmetric orientation around the shaft. Each wing spar beam is inserted into a sleeve unit at the end of a flapping bar connected to the shaft and the V-shaped linkage. This bifurcated angle limiter unit enables the wing to execute passive pitching motion (α) within a predetermined range, subject to aerodynamic and inertial forces. The wings generate lift and axially symmetric thrust during flapping (ϕ) and rotating (ψ) motions due to the inverse Kármán vortex.



(a)



(b)

Figure 4-1 Diagrams of the FWR mechanism integrated with a spring: (a) front view and (b) side view.

Table 4-1 Main components data of the FWR model.

Component Name	Material	Weight (g)	Quantity
Motor	-	4.87	1

Model frame	Polyamide (nylon plastic)	2.76	1
Gear set (4 gears)	Plastics	3.17	1
Rocker	Carbon fibre	0.15	2
Connecting rod and bearing	Carbon fibre, aluminium	0.45	2
Slider and bearing	Aluminium	1.9	1
Bifurcated unit	Aluminium	0.69	2
Vertical shaft	Aluminium	0.9	1
Flapping bar	Carbon fibre	0.3	2
V-linkage	Carbon fibre	0.1	2
Wing rotary bearing	Aluminium	0.3	1
Wing skin	Polyimide	1.33	2
Total	-	19.74	18

4.2.1 Aerodynamic Model of an FWR Wing

To define and describe the FWR wing motion, three successive rigid-body rotations corresponding to rotating, flapping, and pitching motions are illustrated in Figure 4-2(a). The rotation plane of the FWR's wing is horizontal. The rigid-body rotations incorporate the following frames sharing the same origin c : the co-rotating frame $(x_c'' y_c'' z_c'')$ at the point c that is aligned with the inertial frame $(x'' y'' z'')$ at the point o'' of the vertical shaft as the bar of the point c and o'' keeps horizontal, two intermediate frames $(x_1'' y_1'' z_1'')$ and $(x_2'' y_2'' z_2'')$, and the wing-fixed frame $(x_w y_w z_w)$. The wing's rotating, flapping, and pitching angles, donated by ψ , ϕ and α , are also depicted in Figure 4-2(a), respectively.

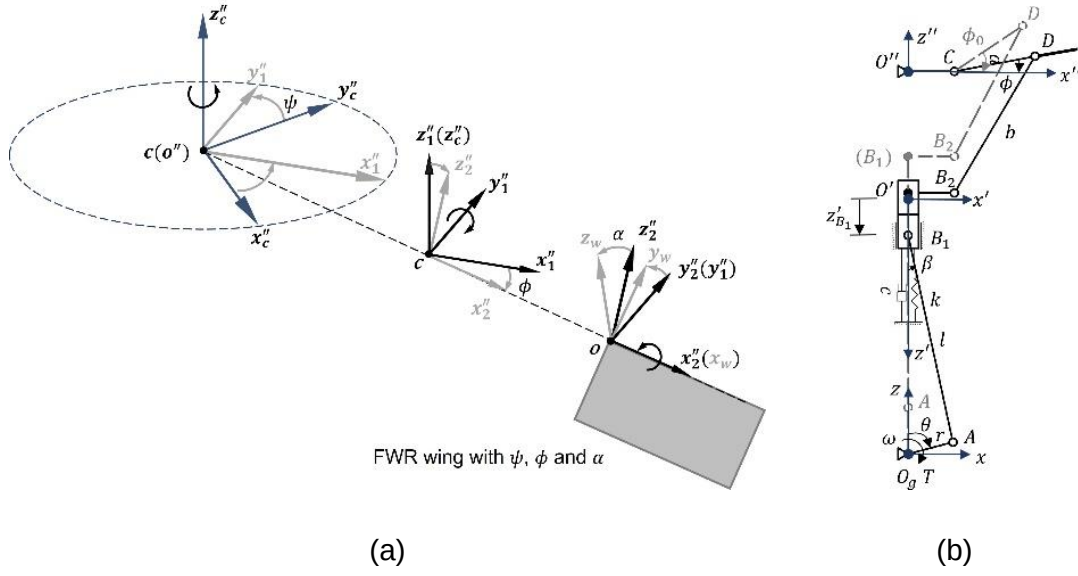


Figure 4-2 (a) Coordinate systems and wing motions of the FWR wing; (b) Mechanical system of the FWR model.

According to the blade element analysis, the rotational velocity and acceleration of a 2D wing strip at the span-wise location r when expressed in the wing-fixed frame can be obtained by the time derivative of ψ , ϕ and α and transformation matrices as follows:

$$\boldsymbol{\omega} = [\omega_x \quad \omega_y \quad \omega_z]^T = (\mathbf{R}_\psi \mathbf{R}_\phi \mathbf{R}_\alpha)^T \begin{bmatrix} 0 \\ \dot{\psi} \\ 0 \end{bmatrix} + (\mathbf{R}_\psi \mathbf{R}_\phi)^T \begin{bmatrix} \dot{\phi} \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \dot{\alpha} \end{bmatrix}. \quad (4-1)$$

The aerodynamic force of FWR is solved by using a quasi-steady (QS) model provided in the previous study (Li et al., 2017). For the morphology of the present FWR wing, the aspect ratio (AR) is defined as the ratio of span (R) over the mean chord ($\bar{c}$). The pitching axis is aligned with the leading edge, thus the distance between the pitching axis and the leading edge (h) is 0. The instantaneous aerodynamic force ($dF_{Aero}(r, t)$) acting on a 2D wing strip at the span-wise location r at an instant time t is a summation of translational force ($dF_T(r, t)$), rotational force ($dF_R(r, t)$), and added mass force ($dF_A(r, t)$), expressed in y_w and z_w directions as follows:

$$dF_{Aero,y}(r, t) = dF_{T,y}(r, t) + dF_{R,y}(r, t) + dF_{A,y}(r, t) \quad (4-2)$$

$$= \{0.5\rho_{air}|\mathbf{U}|^2 C_H c(r) + (\lambda_z u_z \omega_x - \lambda_{z\omega} \omega_x^2)\} dr,$$

and

$$dF_{Aero,z}(r, t) = dF_{T,z}(r, t) + dF_{R,z}(r, t) + dF_{A,z}(r, t) \quad (4-3)$$

$$= \{0.5\rho_{air}|\mathbf{U}|^2 C_V c(r) + C_{rot}|\mathbf{U}|\omega_x c(r)^2 + (-\lambda_z \dot{u}_z - \lambda_{z\omega} \dot{\omega}_x)\} dr,$$

where ρ_{air} is air density; $|\mathbf{U}|$ is the *Euclidean* norm of the translational velocity with $\mathbf{U} = r[\omega_z \quad -\omega_y]^T$, which can determine the effective angle of attack (AoA) denoted by $\alpha_e = \arctan(-\omega_y/\omega_z)$; C_H , C_V and C_{rot} are the QS aerodynamic coefficients due to wing translation and wing pitching (empirical coefficients); λ_z and $\lambda_{z\omega}$ are the added mass coefficients, given by $\lambda_z = \pi/4\rho_{air}c(r)^2$ and $\lambda_{z\omega} = \pi/4\rho_{air}hc(r)^3$. The instantaneous lift (indicated by L) and thrust (indicated by T_t) of an FWR wing are computed by separately integrating $dF_{Aero,z}$ and $dF_{Aero,y}$ of each strip along the wingspan, referenced in the inertial frame ($x''y''z''$).

The mass of a wing strip is denoted by dm_w . The inertial force at the i^{th} wing strip from the tailing edge (TE) to the leading edge in y_w and z_w directions are obtained by the following equations:

$$dF_{Iner,y}(r, t) = \int_{TE}^{LE} (\dot{\omega}_z r + \omega_x^2 y_m) dm_w, \quad (4-4)$$

and

$$dF_{Iner,z}(r, t) = \int_{TE}^{LE} (\dot{\omega}_y r - \dot{\omega}_x y_m) dm_w, \quad (4-5)$$

where y_m is the chord-wise distance between the dm_w and the z_w axis. Then, the resulting forces acting on the 2D wing strip are expressed as follows:

$$dF_y(r, t) = dF_{Aero,y}(r, t) + dF_{Iner,y}(r, t), \quad (4-6)$$

and

$$dF_z(r, t) = dF_{Aero,z}(r, t) + dF_{Iner,z}(r, t). \quad (4-7)$$

Finally, the resulting force $\mathbf{F}_w(t) = [0F_y(t)F_z(t)]^T$ can be derived by integrating the 2D forces of each strip along the wingspan, i.e.,

$$F_{y;z}(t) = \int_0^R dF_{y;z}(r, t). \quad (4-8)$$

In most previous analyses of flapping wings and FWRs, the flapping motion is assumed to be sinusoidal. However, when a DC motor and a crank-slide transmission mechanism drive a loaded flapping mechanism, the motion is no longer purely sinusoidal. To accurately predict aerodynamic forces, it is important to simulate the wing motion of the actual FWR mechanism.

4.2.2 Modelling and Dynamic Analysis of the FWR Model

4.2.2.1 Kinematics

The FWR model depicted in Figure 4-1 can be represented as a mechanical system illustrated in Figure 4-2(b). In this system, a slider B_1 moves linearly along the z'' -axis when driven by a motor through gears, a crank arm O_gA at an angular speed ω ($\dot{\theta}$), and a linkage AB_1 . A spring with stiffness k can be connected between the slider B_1 and a fixed point. Slider B_1 is also connected to flapping bar CD at point D via a pair of linkage bars B_2D and B_1B_2 using pin joints. The dotted line and corresponding joint points depict the maximum displacement of the flapping bar motion constrained by the slider. The o_gyz global coordinate system is established for the kinematic motion of the geared crank, the $o'y'z'$ coordinate system to measure slide B_1 motion, and the $o''y''z''$ coordinate system for the flapping bar, i.e., wing motion.

The displacement of slider B_1 in the local coordinate $o'z'$ for the driving mechanism, can be expressed as:

$$z'_{B1} = r + l - r \cdot \cos\theta - l \cdot \cos\beta. \quad (4-9)$$

As $l\sin\beta = r\sin\theta$ and taking $\lambda = r/l$ as the ratio of the crank arm length r to the connecting rod length l , the kinematic equation of B_1 can be rewritten as:

$$z'_{B1}(t) = r[(1 - \cos(\omega t)) + 0.25\lambda(1 - \cos(2\omega t))]. \quad (4-10)$$

The displacement variation of B_2 along the z -axis is consistent with that of B_1 . In the present FWR model, the length of $O''C$ bar and the distance between B_2 and the central axis are equal. The wing flapping angle can be expressed as:

$$\begin{aligned}\phi(t) &= z'_{B1}(t)/a - \phi_0 \\ &= r[(1 - \cos(\omega t)) + 0.25\lambda(1 - \cos(2\omega t))]/a - \phi_0,\end{aligned}\tag{4-11}$$

where ϕ_0 is the initial flapping angle relative to the slide's limit position, determined by the cosine law. The kinematic description of the passive pitching angle variation of an FWR model has been validated by experiments (Chen et al., 2021). Under the effects of aerodynamic pressure and inertial force, the wing's pitching angle α increased rapidly to its maximum α_{max} at the beginning of the upstroke and remained constant for the rest of the upstroke. Then, during the short period between the end of upstroke and downstroke, the wing rotated oppositely and reached the minimal α_{min} . In the current FWR model, the flapping amplitude is 65° with a $+30^\circ/-35^\circ$ flapping angle. The passive pitch angle varies between 7° and 40° . Experimental results indicate that the rotating frequency is approximately equal to the flapping frequency. For rapid estimation of the FWR model's aerodynamic and inertial forces, it is assumed that the rotating velocity remains constant throughout a flapping cycle.

4.2.2.2 Dynamic Motion Equation of the FWR Model

Featuring gear transmissions, similar to those in Baek et al. (2009) and (Zhang & Deng (2017)), the nonlinear dynamic equation of a DC motor used in the FWR system is,

$$T_{load} + J_e \cdot \ddot{\theta} + B_e \cdot \dot{\theta} = K_u \cdot u\tag{4-12}$$

where T_{load} is the load torque caused by aerodynamic, inertial, and elastic forces; J_e is the total effective moment of inertia of motor and gears; B_e is the effective damping coefficient of the motor's rotating elements; K_u is the linear input gain relative to the gear ratio and the motor's torque constant and resistance. The motor-driven flapping motion is generally excited with sinusoidal input voltage $u = U\sin(\Omega t)$ (Zhang & Deng, 2017; Hines et al., 2014), where U is the

magnitude and Ω is the motor angular velocity. When the crank rotates at a constant angular speed ($\dot{\Omega}, \ddot{\theta} = 0$) without considering the motor and gears' damping ($B_e = 0$), the load torque can directly represent the motor's output torque, $T_{load} = K_u \cdot u$.

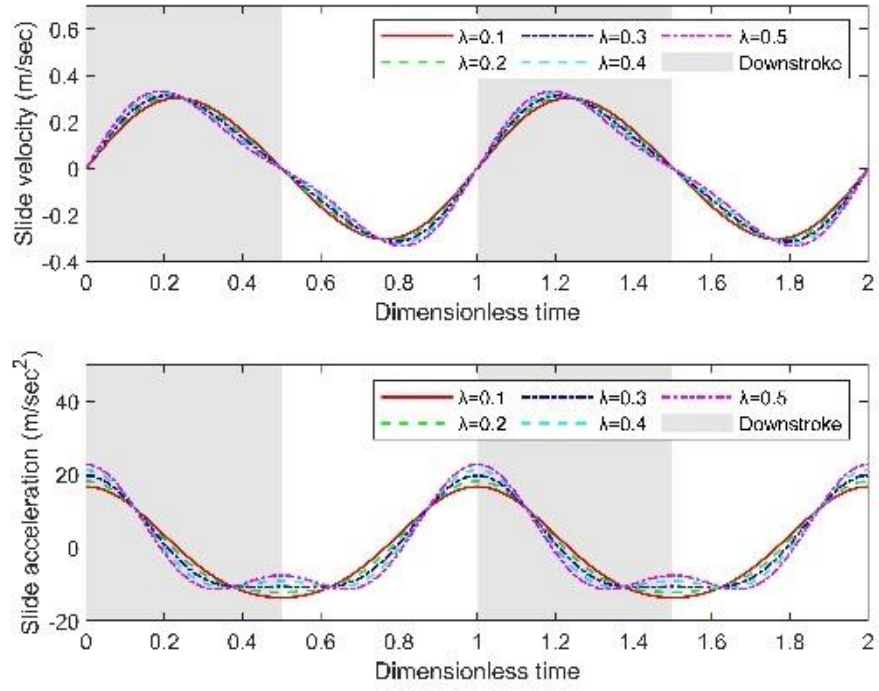
The spring keeps the original length at the halfway point of the slide's travel, $z'_{B1} = r$. The load torque at the instant t applied to the crank-gear mechanism can be expressed as below,

$$T_{load}(t) = \frac{r \sin(\theta + \beta)}{\cos \beta [m_{load} \ddot{z}'_{B1}(t) + k(z'_{B1}(t) - r) + F_{z''}(t)]} \quad (4-13)$$

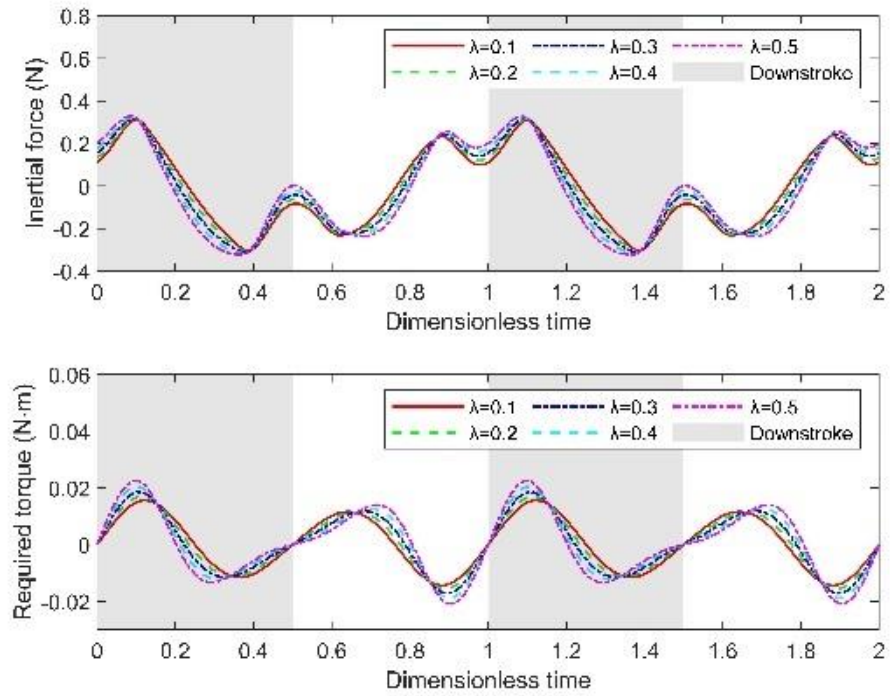
where m_{load} is the mass of load; k is the spring constant ($k = 0$) indicates the baseline model without springs); $F_{z''}(t)$ represents the resulting force $F_w(t)$ of the FWR wing in the z'' axis of the inertial frame.

4.2.2.3 Effect of λ on Kinematics of FWR Motion and Aerodynamics

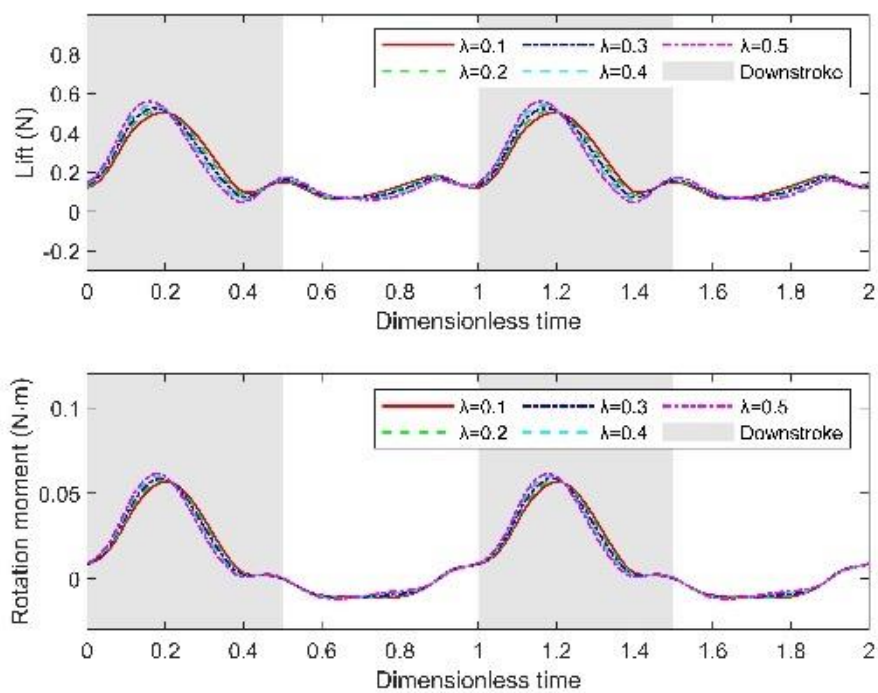
In this FWR mechanism model, the ratio λ between the crank arm and connecting rod significantly impacts the kinematics of the slide and wing, as shown in (4-10) and (4-11), and subsequently influences the required torque for driving the FWR model, as shown in (4-13). Figure 4-3(a)(b) presents the slide velocity, acceleration, wing inertial force and torque results for the system with varying λ values. According to (4-10) for a small angular change ($\Delta\theta$), the slide velocities at the starting position ($t_1 = \Delta\theta/\omega$) and the end ($t_2 = (\pi - \Delta\theta)/\omega$) of the wing downstroke are given by $\dot{z}'_{B1}(t_1) = \omega r(\Delta\theta + \lambda\Delta\theta)$ and $\dot{z}'_{B1}(t_2) = \omega r(\Delta\theta - \lambda\Delta\theta)$, respectively. Since $\dot{z}'_{B1}(t_1) > \dot{z}'_{B1}(t_2)$ for a non-zero λ , the slide reaches maximum velocity before the 1/4 and after the 3/4 cycle periods. A larger λ results in a greater time difference between peak velocities and larger accelerations at the cycle start and end. When λ exceeds 0.3, multiple acceleration peaks occur near the 1/2 cycle period, leading to increased wing inertia force and load torque, as shown in Figure 4-3(b). Conversely, when λ is small enough to be negligible, $\dot{z}'_{B1}(t_1) = \dot{z}'_{B1}(t_2) = \omega r\Delta\theta$, leading to simple harmonic motion, as generally assumed in previous studies.



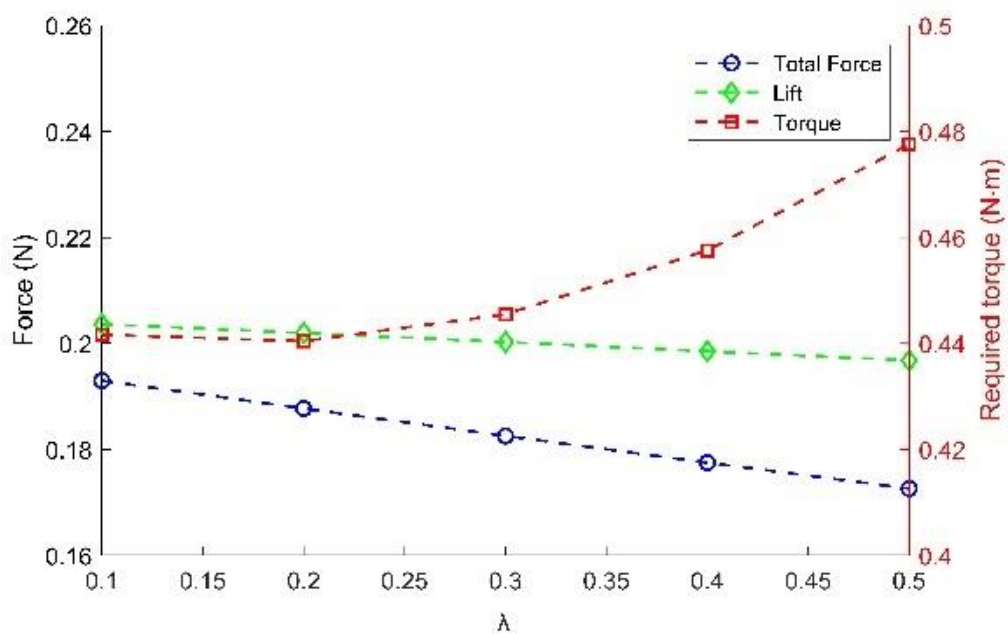
(a)



(b)



(c)

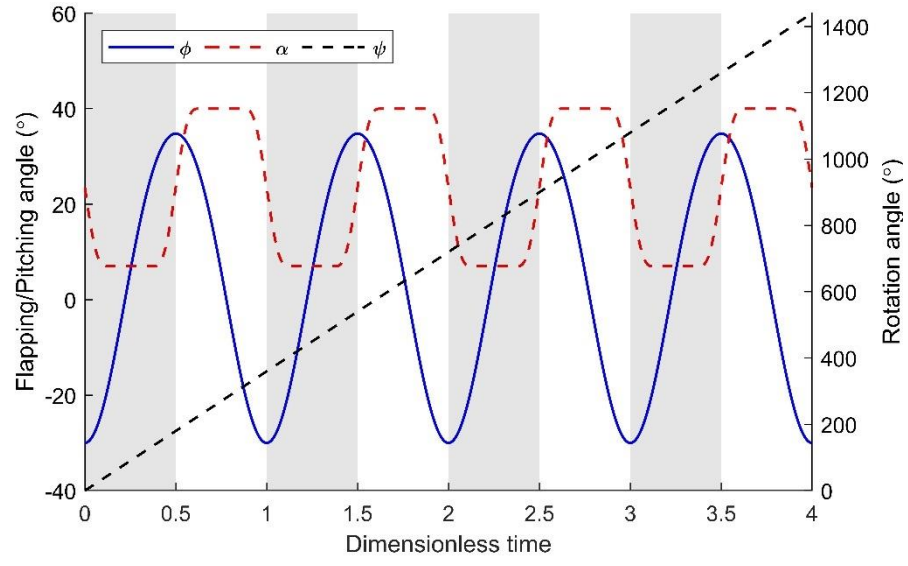


(d)

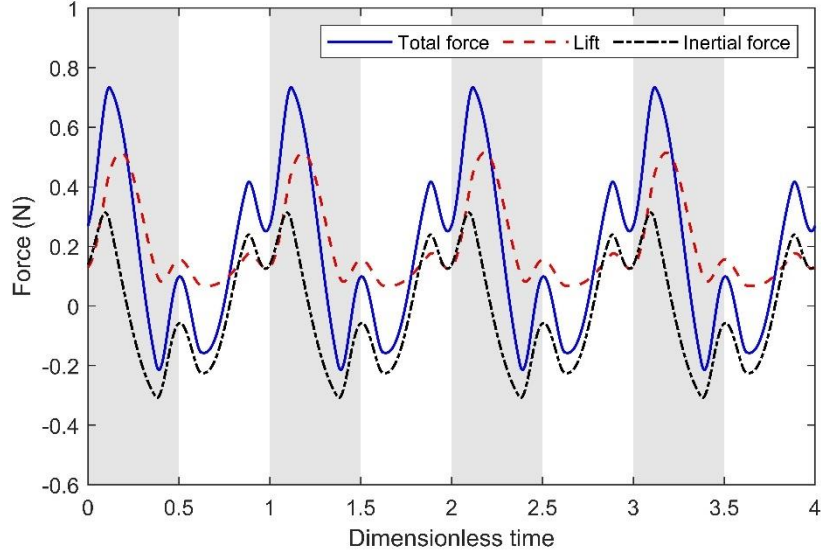
Figure 4-3 (a) Slide velocity and acceleration in $o'y'z'$ coordinates for various λ ; (b) Inertial force in $o''y''z''$ coordinates and required torque for driving the baseline FWR mechanism with different λ ; (c) Variations in instantaneous lift force and rotation moment around the z'' -axis for FWR wings across λ values; (d) Average lift force, total force, and input torque for the baseline FWR model with respect to λ values (referenced in $o''y''z''$ coordinates).

The ratio λ also affects the lift produced by the FWR due to changes in wing kinematics as per (4-2) and (4-3). Figure 4-3(c) demonstrates that the peak values of instantaneous lift force and rotation moment around the z'' -axis of the FWR wing increase with λ . However, the total force, which includes lift and inertial forces, decreases due to the negative inertial force counteracting the lift force during a flapping cycle, as shown in Figure 4-3(d). The required torque increases dramatically when λ is above 0.3. The result shows that the FWR with the largest $\lambda = 0.5$, flapping at the same frequency, generates 11.4% less total force and requires 9% more driving torque compared to when λ is equal to 0.1.

To maintain a compact size and minimum power consumption, $\lambda = 0.22$ was chosen for the FWR test model. As a result, the wing's flapping, pitching and rotating variation at 8 Hz is shown in Figure 4-4(a). The increase in passive pitching angle during the upstroke corresponds to the decrease in forces, especially lift, as shown in Figure 4-4(b). The maximum and minimum values of lift and inertial force occur during the transition from downstroke to upstroke when the wing pitching angle changes from 7° to 40° to produce additional downward thrust.



(a)



(b)

Figure 4-4 (a) Kinematics of wing motions and (b) total force, inertial force and lift force of the baseline FWR model (with reference $\mathbf{o''y''z''}$ coordinates, 8 Hz and $\lambda = 0.22$).

4.2.2.4 Effect of Resonance and Spring Stiffness

As the wing inertial force is proportional to the acceleration $\ddot{z}_{B1}'(t)$, a nondimensional torque $\hat{T}_{load}$ can be defined from the torque equation (4-13) divided by the mass moment of inertia times ω_n^2 , i.e. $\hat{T}_{load} = T_{load}/(m_e r^2 \omega_n^2)$ as follows:

$$\begin{aligned} \hat{T}_{load}(\hat{t}) = & \delta(\hat{t})\{(\omega^2/\omega_n^2)[\cos(\hat{t}) + \lambda \cos(2\hat{t})] \\ & + [-\cos(\hat{t}) + 0.25\lambda(1 - \cos(2\hat{t}))]\} \\ & + \delta(t)F_{Aero,z}/(m_e r^2 \omega_n^2), \end{aligned} \quad (4-14)$$

where $\hat{t}$ is the nondimensional time $\hat{t} = \omega t$; the effective mass m_e refers to the sum of m_{load} and the FWR wing's inertial mass; the natural frequency of the system in resonance can be predicted by $\omega_n = \sqrt{k/m_e}$; $\delta(t)$ can be simplified as

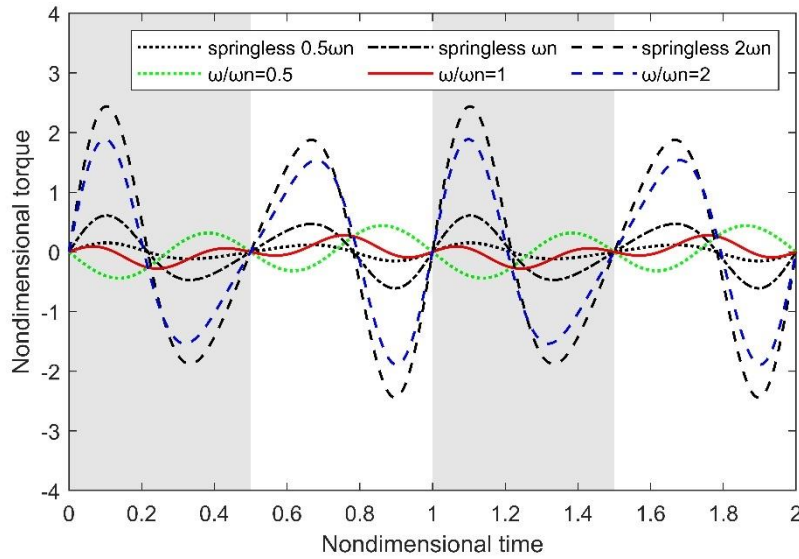
$$\begin{aligned} \delta(\hat{t}) = & \sin(\theta + \beta)/\cos\beta \\ \approx & \sin(\hat{t}) + 0.5\lambda \sin(2\hat{t})/(1 - 0.5\lambda^2 \sin^2(\hat{t})) \end{aligned} \quad (4-15)$$

Since the kinematic motion of the FWR test mechanism with a small λ is close to simple harmonic. When the system achieves resonance, i.e., $\omega = \omega_n$, only the aerodynamic term remains against the torque in equation (4-14) if neglecting the mechanical damping since the elastic force and the inertia force would be cancelled against each other. This would be an ideal case where the required torque from a motor is reduced to the minimum to overcome the mechanical damping force and the aerodynamic force only.

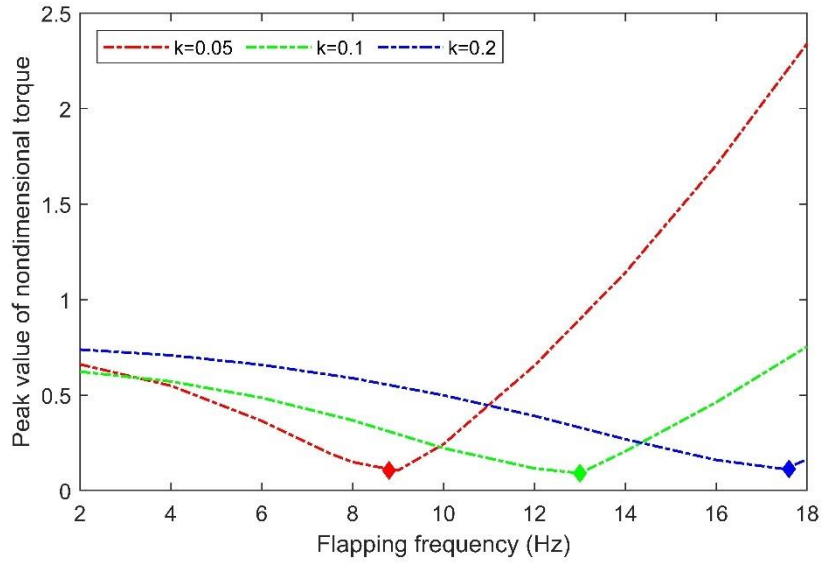
The power efficiency of the FWR model at a flapping frequency is defined by $P_e = L/P$, where P is the input power from a motor (W). In the analytical model, the power efficiency is evaluated by the lift and required torque, i.e., $P_e^* = L/T_{load}$. A power-saving value considering the spring effect can be calculated by $S_p = (P_0 - P_s)/P_0 \times 100$ (%), where P_s and P_0 represent the required power (torque) for the model with and without spring respectively.

In the mechanical system without considering aerodynamic force, the required torque $\hat{T}_{load}$ against ω/ω_n is shown in Figure 4-5(a). At resonance $\omega/\omega_n = 1$, the torque $\hat{T}_{load}$ is minimised at $\lambda\delta(\hat{t})(0.25 + 0.75\cos(2\hat{t}))$. Compared to the baseline

model at a natural frequency ω_n , the peak torque of the model with a spring (0.05 N/mm) is reduced by 54% (i.e., $S_p = 54\%$). When the frequency exceeds the ω_n , the required torque increases with frequency, such as $\omega/\omega_n = 2$, but remains smaller than the baseline model ($S_p = 23\%$) without a spring. The natural frequencies of the FWR model with spring stiffness of 0.05 N/mm, 0.1 N/mm, and 0.2 N/mm can be determined from the minimum peak torque results, which are 8.8 Hz, 12.8 Hz, and 17.5 Hz, respectively, as shown in Figure 4-5(b). This figure also highlights the significant impact of spring stiffness on the required torque. The model with lower spring stiffness such as 0.05 N/mm requires less torque at lower flapping frequency, while higher stiffness such as 0.2 N/mm requires considerably less torque at higher frequencies.

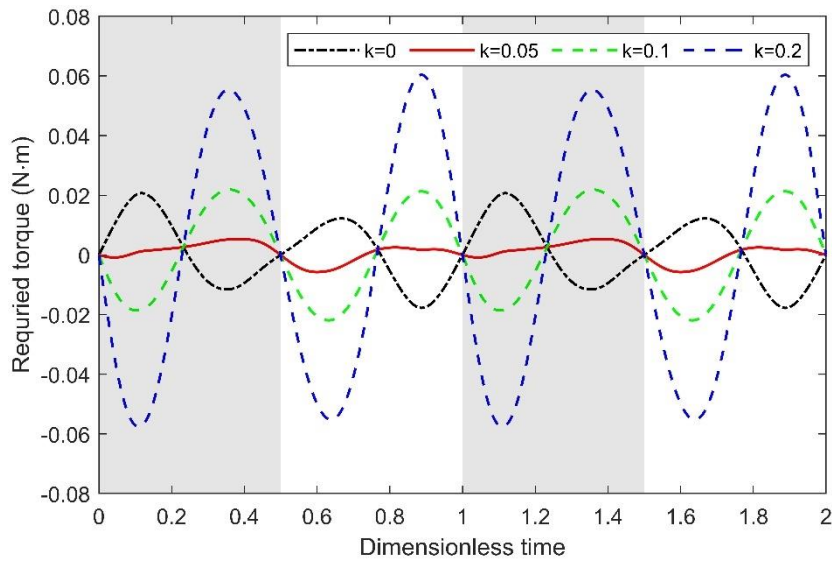


(a)

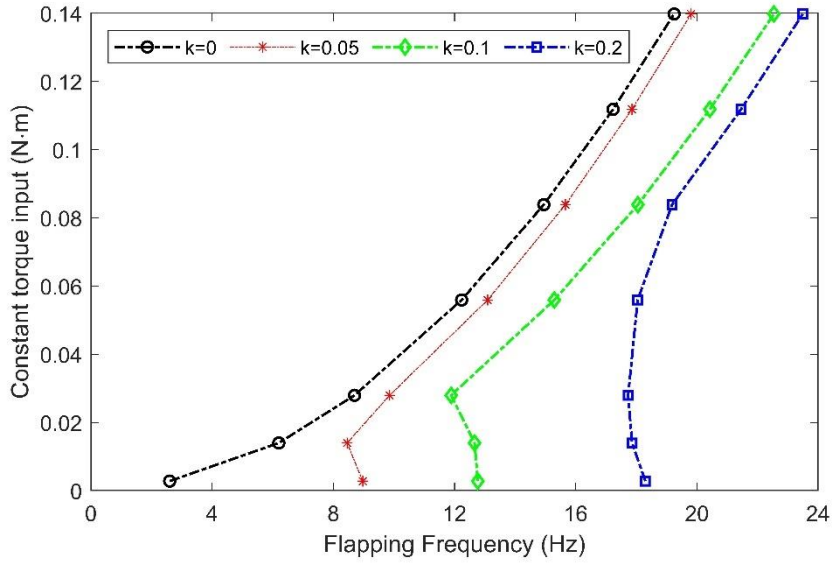


(b)

Figure 4-5 (a) Variation of the required nondimensional torque with nondimensional time in a range of ω for the model with a spring ($k = 0.05$ N/mm), compared with the springless baseline model at $0.5\omega_n$, ω_n and $2\omega_n$ ($\lambda = 0.22$); (b) Nondimensional torque versus flapping frequency of the model with different springs.



(a)



(b)

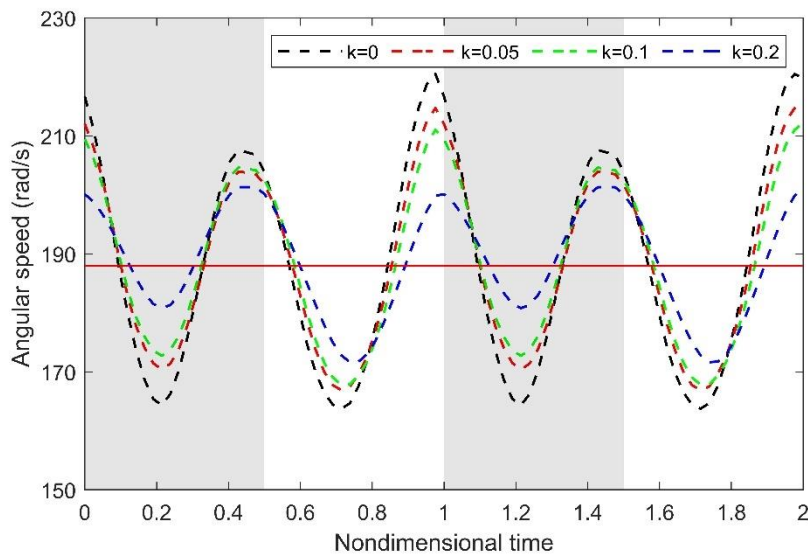
Figure 4-6 (a) Required torque of the FWR model with different spring stiffness compared with the baseline model at flapping frequency 8 Hz while producing the same amount of aerodynamic force ($\lambda = 0.22$); (b) Input torque for the FWR models of different spring stiffness compared with the baseline model at different flapping frequencies.

When aerodynamic force is considered, the torque to drive the FWR flapping at 8 Hz for different springs is shown in Figure 4-6(a). In this case of constant ω , the aerodynamic force produced by the baseline model and spring models is the same. Since the resonance frequency of the model with 0.05 N/mm spring is close to 8 Hz, the required torque is the smallest compared to other models. Before the mid-downstroke (in the grey area as seen in Figure 4-2(a)), the spring is stretched, providing an elastic force that contributes to the wing flapping motion, resulting in a negative torque. After the second half of the downstroke, the spring is compressed, leading to an increase in positive torque, and vice versa for the upstroke.

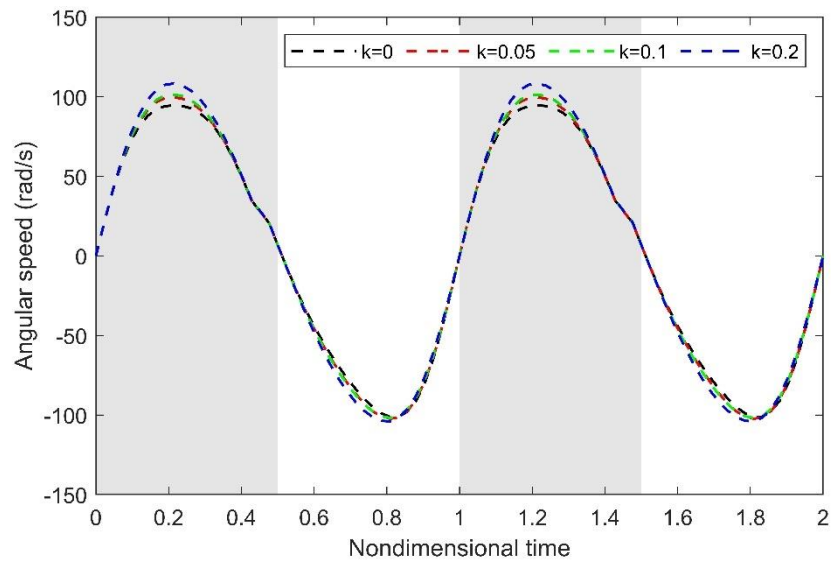
At a given flapping frequency, the kinematics of flapping motion remain consistent for the model, regardless of the spring, but flapping velocity and acceleration are affected. Ideally, excessive spring potential energy should be transferred back to

the motor for later use (Tantanawat & Kota, 2007; Baek et al., 2009), but it is impractical to save energy directly through a DC motor. Thus, a constant input voltage/torque is assumed for a motor-driven flapping-wing robot (Baek et al., 2009). In reality, a DC motor is unable to maintain a constant rotating speed without a speed controller. Consequently, the counter electromotive force from the DC motor produces a negative torque against the excessive energy and causes an increase in the motor power. Therefore, a constant torque rather than a constant speed is set in the study to simulate the spring effect on both the kinematic motion of the wing and the power requirement.

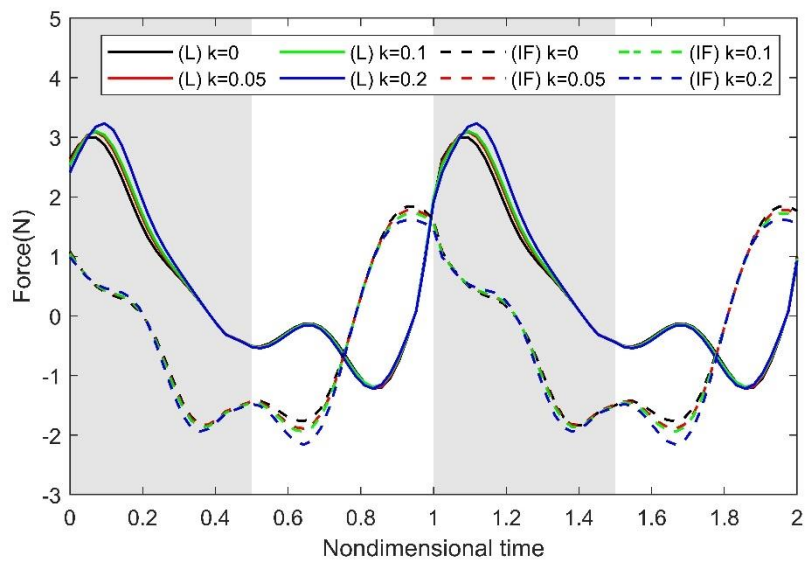
The least squares method is employed to solve the non-linear dynamic equation of the FWR model (4-13), determining the torque input from the motor versus the flapping frequency, as shown in Figure 4-6(b). The minimum input torque for the baseline model and models with spring stiffness 0.05 N/mm, 0.1 N/mm, and 0.2 N/mm occurs at 2.5 Hz, 8.89 Hz, 12.5 Hz, and 17.9 Hz, respectively, aligning with the resonant frequencies of the models. Under the same input torque, the flapping frequency of models with springs is greater than the baseline model and increases with stiffness. Consequently, the aerodynamic and inertial forces generated by the FWR models with springs are larger than the baseline model.



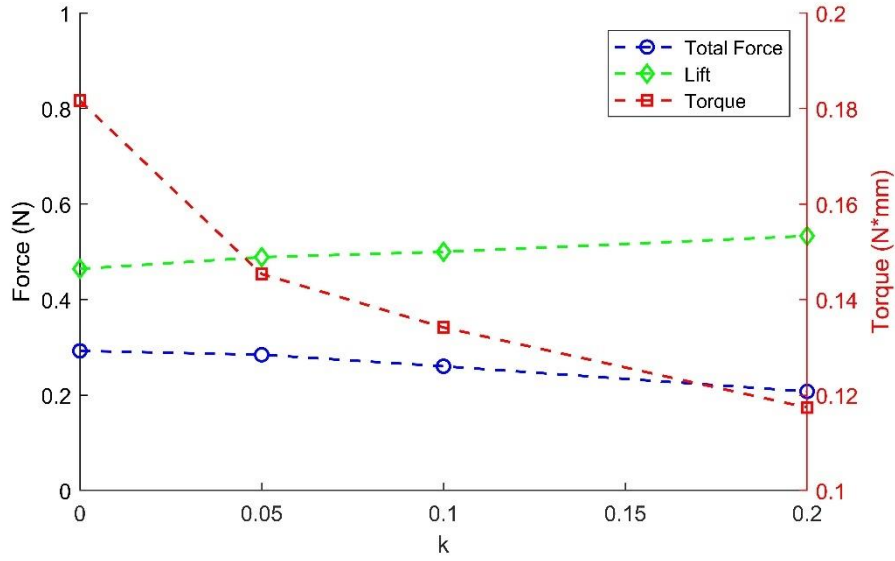
(a)



(b)



(c)



(d)

Figure 4-7 (a) Variation of the crank angular speed ω ; (b) Wing flapping angular velocity $\dot{\phi}$; (c) Inertial force (denoted by IF) and lift (denoted by L) of models with different spring stiffness; (d) Time-averaged total force, lift and the driving torque change with spring stiffness (the crank angular speed and the wing kinematics and forces are expressed in xyz and $x''y''z''$, respectively).

As each model exhibits distinct flapping frequencies under the same input constant torque, the kinematics and forces of the spring models are compared to the baseline model at a selected time-averaged crank angular velocity of approximately 188 rad/s (around 30 Hz), as demonstrated in Figure 4-7. Given a constant input torque, the transmission crank's angular speed varies periodically, and the amplitude is smaller with larger spring stiffness (Figure 4-7(a)). Consequently, the FWR flapping angular velocity results in Figure 4-7(b) indicate that the peak value difference between the models about 5%-10% is much smaller than the crank speed difference.

The FWR model with the highest spring stiffness of 0.2 N/mm exhibits the largest positive peak value of flapping angular speed near the middle of the downstroke which contributes to the lift force as shown in Figure 4-7(c). During upstroke, the

difference in peak inertial force becomes larger. Figure 4-7(d) reveals that as FWR model spring stiffness increases, aerodynamic lift force experiences a slight increase, while the required torque is significantly reduced. In this case of such high flapping frequency, spring stiffness of 0.05 N/mm, 0.1 N/mm and 0.2 N/mm results in a power reduction for the model by $S_p = 20\%$, 26%, and 35%, respectively, compared to the baseline model producing an approximately equivalent lift of 0.5 N. The FWR model with the spring stiffness of 0.2 N/mm can achieve a power efficiency of $P_e^* = 4.54/m$, which is 77% higher than that of the baseline model ($P_e^* = 2.56/m$).

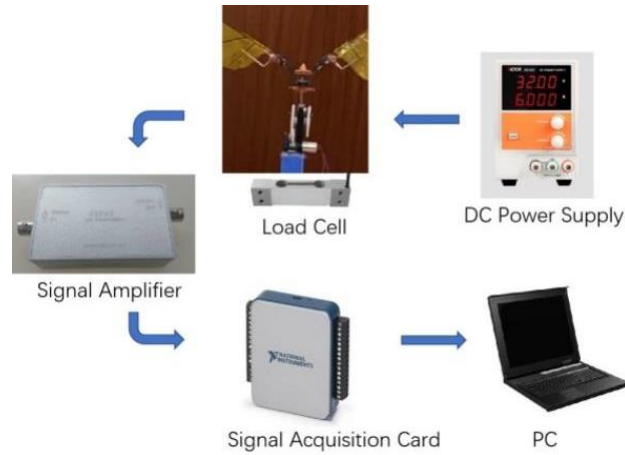
4.3 Experiment Results and Discussion

4.3.1 FWR Model Test Setup

An experimental platform and FWR test model were constructed using the components depicted in Figure 4-8 to assess the FWR model's transverse dynamic force. The FWR model performed the motions as illustrated in Figure 4-4(a). The single wing spanned 165 mm with a maximum chord of 60 mm. A DC motor drove the FWR model, which was mounted on a high-precision load cell device (capacity 200 g, inaccuracy 0.05 percent F.S). A DC supplier provided power. The load cell's output voltage signal was amplified (gain 1k) and sent to a data acquisition device (NI USB-6009), with data processed by LabVIEW software to obtain the FWR model's total force.



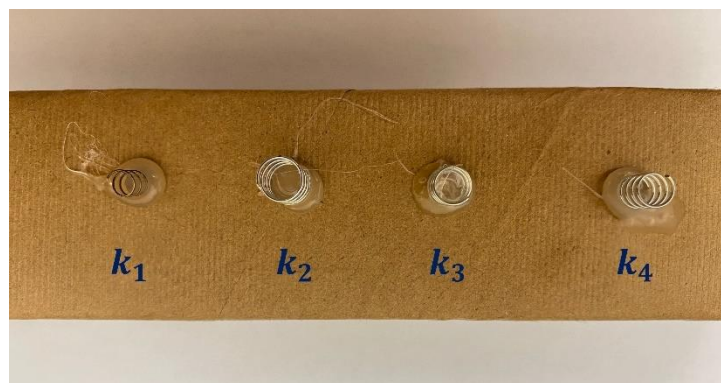
(a)



(b)

Figure 4-8 (a) FWR physical model; (b) Experiment setup for force measurement.

Informed by the analytical study, a range of different spring stiffness $k_1 = 0.036$, $k_2 = 0.055$, $k_3 = 0.11$, and $k_4 = 0.22$ N/mm was selected for the experiment (Figure 4-9(a)). The spring was split into two, one above and the other below the slider (Figure 4-9(b)). When the slider was in the middle position ($\theta = 90^\circ$), both springs were in their neutral position with their original length. When the slider moved to the second half of the downstroke (wing downstroke too), the lower spring compressed (Figure 4-9(c)). The spring returned to neutral after the first half of the upstroke and then compressed in the second half (Figure 4-9(d)). The springs in the model work in the same manner as the springs set in the analytical model.



(a)

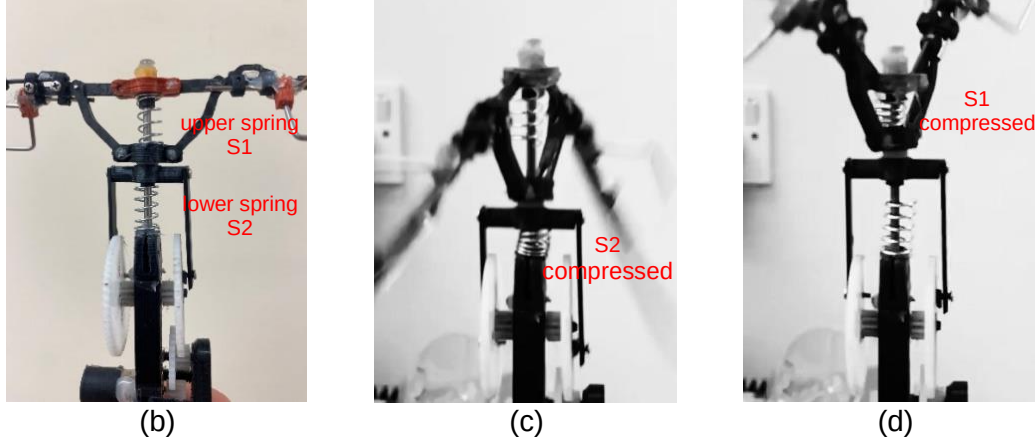
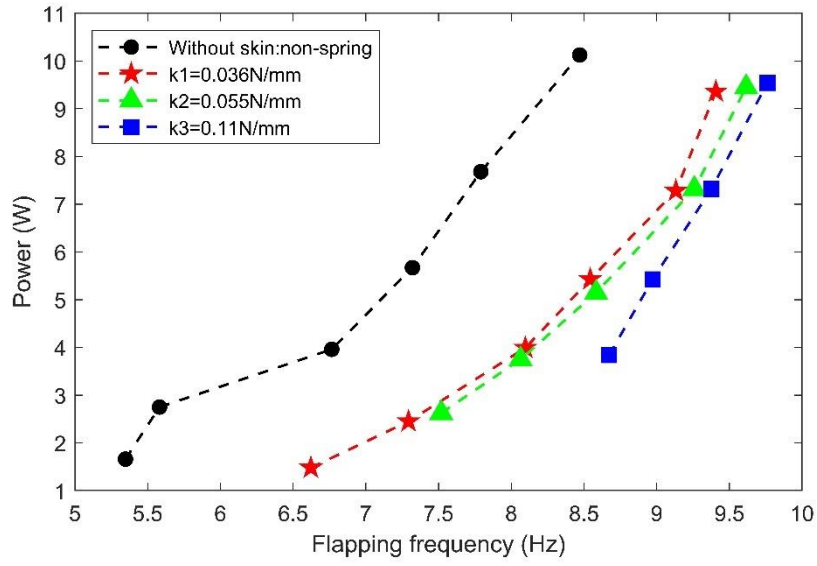


Figure 4-9 (a) Four springs of stiffness $k_1 = 0.036$, $k_2 = 0.055$, $k_3 = 0.11$, and $k_4 = 0.22$ N/mm; FWR model with (b) springs in original length, (c) the lower spring in compression, (d) the upper spring in compression.

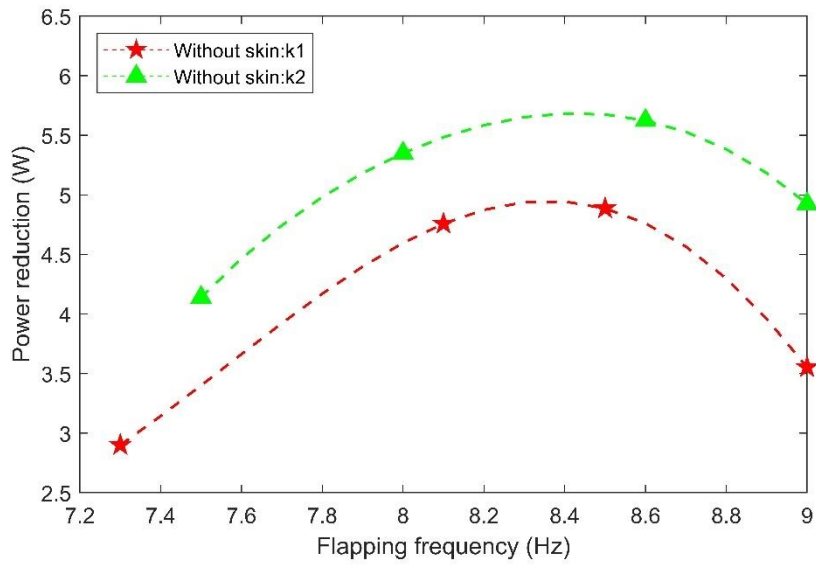
4.3.2 Experiment of the Pure FWR Mechanism

In the first test case, the skin membrane was removed from the wing to eliminate aerodynamic force. The experiment focused on a range of input power (1.5 W to 10 W) and flapping frequency (5 Hz to 10 Hz). With spring stiffness k_4 , the FWR mechanical system was ineffective at the tested low flapping frequency range due to higher power requirements to be driven. Consequently, the experiment focused on samples with lower spring stiffness values, specifically k_1 to k_3 . Figure 4-10(a) demonstrates that the system with springs required less input power than the baseline at any flapping frequency. Input power increased with spring stiffness, as did flapping frequency for a given input power.

Figure 4-10(b) shows the power reduction $\Delta P = P_0 - P_s$ for k_1 and k_2 springs across a wide frequency range, including their resonance. Maximum reduced input power ΔP for k_1 and k_2 systems was 4.94 W and 5.68 W, with power savings S_p of 49.4% and 53%, respectively. The results also indicate that 8.35 Hz and 8.45 Hz correspond to the resonance frequencies of the two test systems, achieving maximum power reduction. Analytical resonance results (7.85 Hz and 9.26Hz) differed by 6.37% and 8.75% from test models, respectively.



(a)

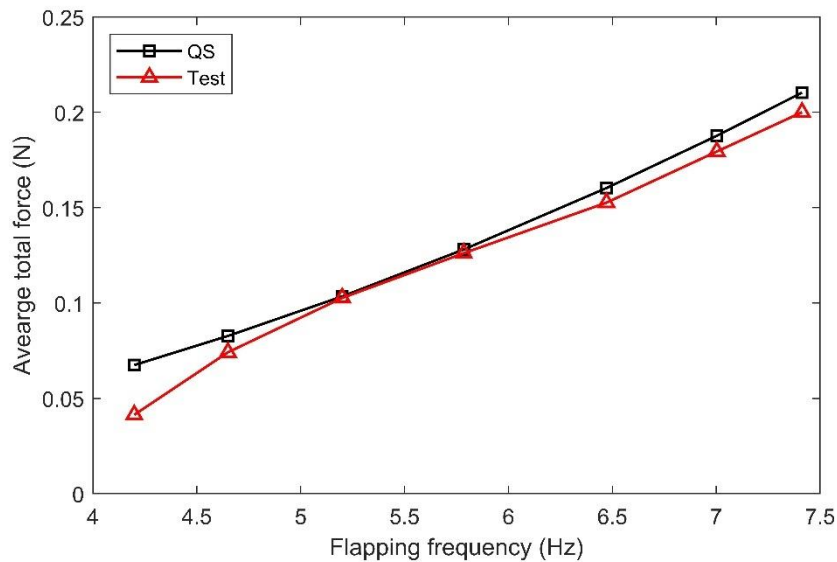


(b)

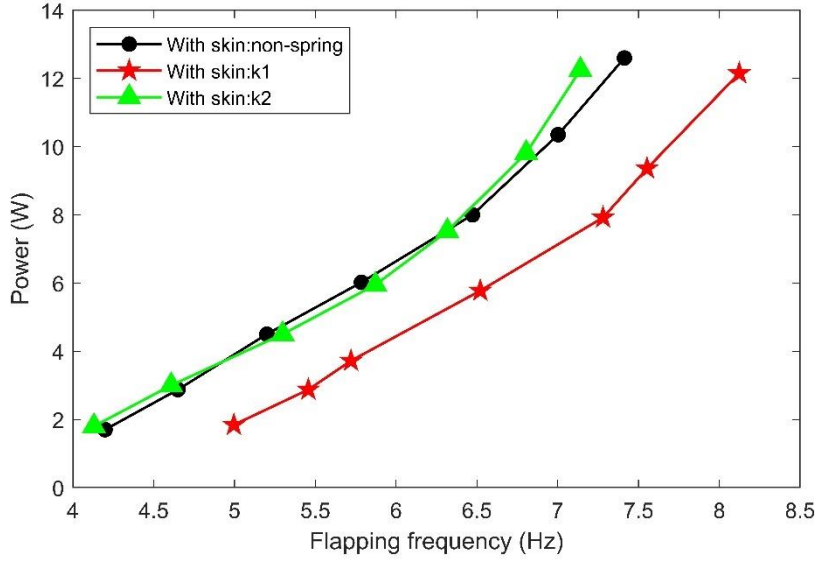
Figure 4-10 (a) Input power and (b) power reduction of the FWR mechanical system with k_1 and k_2 springs within a range of flapping frequencies.

4.3.3 Experiment of the FWR Model Including Aerodynamics

In the second test case, the wings were covered with skin membranes. Despite the measured instantaneous total force of the FWR model encompassing both aerodynamic and inertial forces, the average inertial force over a flapping cycle equaled zero. As shown in Figure 4-11(a), the analytical average aerodynamic lift force closely matched the measured average total force of the baseline FWR model across various flapping frequencies. Figure 4-11(b) demonstrates that after the generation of aerodynamic forces, the power required to drive the FWR model with wing skin is approximately double that of the baseline system without wing skin (Figure 4-10(a)). The input power for the baseline and k_2 spring models increased almost linearly below 6.5 Hz, with a sharper increase thereafter. The k_1 spring model followed a similar trend, with a steeper increase after 7.3 Hz. The required power for the k_1 spring model was about half of the baseline model and the k_2 spring model. Limited data was obtained for models with k_3 and k_4 spring stiffness due to power demands exceeding motor capabilities.



(a)



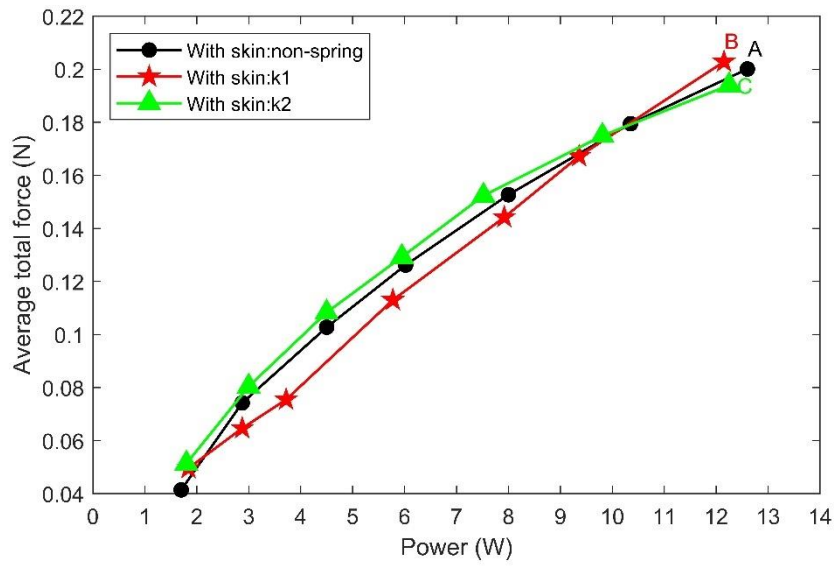
(b)

Figure 4-11 (a) Comparison of measured and analytical average total force for the baseline FWR model; (b) Required input power for FWR test models with wing skin and varying spring stiffness across a range of flapping frequencies.

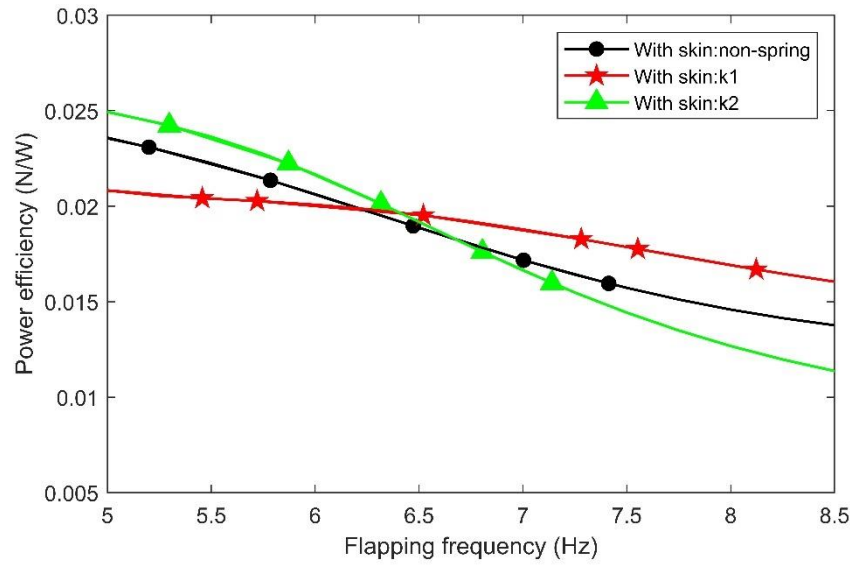
Figure 4-12(a) demonstrates the increasing measured average total force with input power. The k_1 spring model exhibited slightly lower average total force compared to the baseline and k_2 spring models within the 2 W to 10.35 W input power range. As the average inertia force in a flapping cycle is negligible, these results represent average aerodynamic lift force. Furthermore, Figure 4-12(a) indicates that at an input power of around 12 W and a DC supply voltage of 5 V, the average total forces for the FWR baseline model and models with k_1 and k_2 springs are 20.4 g, 20.7 g, and 19.8 g (points A, B, C), respectively. Considering the FWR test model's weight of 19.74 g, it can achieve vertical take-off.

Figure 4-12(b) shows the power efficiency (P_e) of FWR models, defined as the average total force to input power ratio (N/W). Power efficiency for all models decreased with increasing flapping frequency between 5 Hz to 8.5 Hz, with the k_1 spring model exhibiting the smallest reduction rate. At frequencies below 6.5 Hz, the k_2 spring model demonstrated greater efficiency, attributable to increased

aerodynamic force resulting from larger acceleration due to greater elastic force, despite higher power requirements for spring deformation. However, for frequencies above 6.5 Hz, the power required to deform the same spring significantly increased, making the k_2 spring model less efficient than the k_1 spring model. For instance, the k_1 spring model's power efficiency at 8.1 Hz is $P_e=0.017$ N/W, 16% higher than the baseline model and 33% higher than the k_2 spring model.



(a)



(b)

Figure 4-12 (a) Measured average total force for models as a function of input power; (b) Power efficiency across various flapping frequencies.

4.3.4 Take-off Flight of the FWR Model with Onboard Power

To demonstrate the feasibility of FWR model flight, the FWR test model, as shown in Figure 4-8, was equipped with an onboard battery and control device (receiver) for flight testing. The components of the FWR mechanism are outlined in Figure 4-1 and Table 4-1. The FWR mechanism is powered by a 3.7 V DC motor, which is connected to a receiver which operates on a lithium battery (3.7 V, 150 mAh, maximum 25 C discharge current). The power and speed of the wing flapping, which influence the altitude gain, are regulated by the throttle stick on the radio transmitter. The weights of these hardware components are detailed in Table 4-2, resulting in the model's total take-off weight being 27.79 g.

The vertical take-off of the FWR model is shown in Figure 4-13. Compared to the initial 2.6 g FWR prototype model that achieved vertical take-off in 2017 (Guo et al., 2018), the current flight test model has nearly doubled the wing area and generated ten times greater lift.

Table 4-2 List of the flight test onboard devices.

Component Name	Size	Unit Weight (g)	Number
3.7 V 4000 rpm DC motor	diameter 8.5 mm, length 20.3 mm	4.87	1
25C 150mAh 3.7 V lithium battery	28 × 20 × 7 mm	6.05	1
Ma-RX43E-A2 receiver	22.5 × 12 × 6.5 mm	2	1



Figure 4-13 Vertical take-off flight test of the FWR-MAV model.

Considering the battery's maximum operating current of 3.75 A, the 27.79 g FWR model requires 13.9 W of power for take-off. The required input power and flapping frequency are slightly above the experimental range shown in Figure 4-12. Given that the FWR model successfully achieves take-off flight, its power efficiency P_e is calculated to be 0.02 N/W. In a previous tethered flight model (Chen et al., 2021) with similar weight (22.7 g without battery), the coreless motor had a continuous power of 15 W and a rated voltage of 7.4 V. Since 9 V from a DC supply was used for its take-off, the input power exceeded the motor's rated power. On the other hand, based on the rated current, at least 18.24 W was needed for the 22.7 g model to take off, with a power efficiency P_e of 0.012 N/W. Therefore, it indicates that the current FWR-MAV model's power efficiency has improved by 66.7% compared to the previous tethered flight model.

4.4 Conclusion

This study demonstrates the significant enhancement of FWR power efficiency using an elastic flapping mechanism, employing both analytical and experimental approaches on a potentially flyable FWR model. The resonant frequency is determined based on the mechanical system's mass distribution and spring stiffness. The analytical model highlights that the input power can be reduced by 50% at resonance in comparison to the baseline system without a spring. Furthermore, incorporating an optimally stiff spring can lead to a 20%-35% reduction in power consumption and an increase in power efficiency by up to 77% at high flapping frequencies.

From the experimental study, the following key findings are drawn:

- Analytical model validation through experimentation.
- 49.4% input power reduction for the mechanical system (no wing skin) with a 0.036 N/mm spring stiffness at the resonant frequency of 8.35 Hz.
- 14% input power reduction and 16% power efficiency increase for the FWR model with wing skin and a 0.036 N/mm stiffness spring at 8.1 Hz flapping frequency compared to the baseline model.
- Additional power required for aerodynamic lift force generation compared to the mechanical system without skin.
- 20% less power consumption and a 66.7% increase in power efficiency compared to a previous FWR model with the same level of weight and size.
- The FWR-MAV has successfully achieved controlled free flight with an onboard power unit and remote-control device, demonstrating significant progress in terms of increasing the flight endurance and payload capability for FWR-MAVs' potential application.

Chapter 5 21 Aerodynamic Performance of a Flapping Wing Rotor with Dragonfly-like Flexible Wing

Acknowledgement: In this chapter paper, the author's colleague, Xun Huang, was responsible for conducting the flight tests of FWR models, as shown in Figure 5-21 in Section 5.3.5.

Abstract

Drawing inspiration from insect flapping wings, a novel flapping wing rotor (FWR) has been developed for micro aerial vehicle (MAV) applications, featuring unique flapping and rotary kinematics to achieve high flight efficiency. This study thoroughly investigates the aerodynamic performance and design of a bio-inspired flexible wing for FWR-MAVs, emphasizing its novel backward-curved wingtip and variable spanwise stiffness resembling a dragonfly's wing. The research departs from previous aerodynamic studies of FWR, which focused predominantly on rectangular and rigid wings, and delves into wing flexibility. Employing computational fluid dynamics (CFD), computational structural dynamics (CSD), and experimental measurements, the study demonstrates the aerodynamic benefits of the dragonfly-inspired wingtip shape and its reinforced structure. Fluid-structure interaction (FSI) analysis is used to examine the effects of elastic deformation encompassing twist and bend on aerodynamic forces. The results underscore the importance of bending deformation in enhancing lift and power efficiency and propose a method for analysing variable stiffness along the wingspan using a vortex delay mechanism that is induced by delayed flapping motion. By comparing modelled and measured stiffness, the study validates the flexibility of the FWR wing, revealing optimal aerodynamic efficiency is achieved through moderate flexibility and spanwise stiffness variation. The curving leading-edge beam forming the sweep-back wingtip offers a practical approach to obtaining variable stiffness and aerodynamic benefits for FWR-MAVs. Using the same pair of dragonfly-like flexible wings, FWR-MAVs have effectively exhibited VTOL and hovering flight capabilities, spanning from a 25 g single-motor drive model to a 51 g dual-motor drive model. This research provides valuable insights

into flexible wing design for FWR-MAVs, leveraging biomimicry to improve flight efficiency.

Keywords: Flapping wing rotor (FWR), Flexible wing, Fluid-structure interaction (FSI), Aerodynamics, Power efficiency

5.1 Introduction

Biomimetic micro air vehicles inspired by the flapping flight of insects have attracted a lot of attention in recent years. Many flapping wing micro aerial vehicles (FW-MAVs) have been extensively developed, however due to the characteristics of low Re flight, the existing vehicles still have limitations regarding lift generation and power efficiency (Chin & Lentink, 2016; Petricca et al., 2011; Phan & Park, 2019). To date, studies on a novel flapping wing rotor (FWR), which incorporates active flapping with passive rotation motions of the asymmetrically installed wings, have grown in importance as a way of improving the aerodynamic performance of FW-MAVs (Li et al., 2017; Li & Guo, 2018). The evidence presented in previous research suggests that at an equivalent level of power efficiency, the lift produced by the FWR wing can be twice as high as that produced by a rotary wing (Li et al., 2017); the aerodynamic efficiency of the FWR wing is much higher than the typical insect-inspired flapping wings (Li et al., 2011; Guo et al., 2018). Nevertheless, when examining earlier FWR-MAV designs, most of the wings did not employ a bio-inspired configuration but rather a simple rectangular plate. The effects of a bionic wing shape and flexibility on aerodynamic forces and efficiency have not been studied in detail for FWR-MAVs.

The insect wing, unlike the wing of a bird, lacks muscles and is therefore subject to passive deformation, which primarily is composed of transient spanwise bending, twist, and chordwise camber variation. For conventional flapping wings, wing deformation and flexibility have been extensively studied. The wing deformation is significantly determined by the elastic responses to aerodynamic and inertial forces (Phan & Park, 2018; Wootton, 2020). Proper deformation of the flapping wing can improve aerodynamic performances in terms of lift-to-drag ratio (Vanella et al., 2009), flight efficiency (Young, 2012), and reducing the

energy costs (Shahzad et al., 2018). As the flexibility of a flapping wing has considerable effects on its aerodynamic characteristics (Liani et al., 2007; P. Wu et al., 2009), a moderate stiffness should be adopted in order to achieve high lift and propulsive efficiency (Chen et al., 2022; Heathcote & Gursul, 2007). Specifically, Heathcote et al. (Heathcote et al., 2008) discovered that in a water tunnel study, a degree of spanwise flexibility contributed to a slight increase in thrust coefficient and a slight drop in power requirements, resulting in greater efficiency for Strouhal numbers above 0.2. Similarly, Yang et al. (2019) showed in their experimental study that the span stiffness has a significant effect on the lift generation, while the chordwise stiffness has a greater impact on the thrust generation.

The aerodynamic performance of flexible flapping wings is also affected by the wing geometry, including the wing shape and aspect ratios, as well as the wing structure. For example, increasing the aspect ratio and root cut-off of a flexible flapping wing can improve lift production during hovering flight, as found by a previous study (Chen et al., 2022). Nan et al. (2017) found that a trapezoidal shape, a straight leading edge, and an aspect ratio of 9.3 can achieve excellent performance for a hummingbird-sized wing. However, an analysis of flapping wings with various shapes has also revealed that high aspect ratio wings, such as those with aspect ratios of 4.5 and 6.0, provide less lift than rigid wings due to lower pitch angles during the mid-stroke (Shahzad et al., 2018). These results indicate that the findings on wing shape and aspect ratio may be restricted to specific case studies and might not be universally applicable to all flapping models, particularly not for FWRs, which exhibit unique kinematics compared to traditional flappers.

Multiple studies have demonstrated that reinforced structures, such as a rigid leading edge, a reinforced trailing edge, a rigid triangle at the wing root, and diagonal battens, can be incorporated into flexible wing designs (Phillips et al., 2015; Shahzad et al., 2018b; Wu et al., 2010). However, most flapping wing structures are assumed to have approximately isotropic homogeneous flexibility (Eldredge et al., 2010; Shahzad et al., 2016, 2018) or anisotropic flexibility but

uniform torsional or bending stiffness (Wang et al., 2017; Zhao et al., 2010), and often neglect the effects of wingtip and mass lump in the analysis. In contrast, the current study focuses on a dragonfly-like flexible FWR wing, which features variable stiffness along the wingspan and a curving leading-edge beam that reinforces the wingtip.

Recent studies have highlighted the non-trivial mechanisms governing the aerodynamic performance of flexible wings, including the delayed burst of the leading-edge vortex (Phillips et al., 2015; Godoy-Diana & Thiria, 2018; Nakata & Liu, 2012), and delayed pitch rotation (Shahzad et al., 2018; Nakata et al., 2018). These effects have been shown to enhance lift production. In this study, we investigate, to our knowledge for the first time, the delayed flapping motion by which wing spanwise flapping deformation governs lift enhancement for an FWR model.

The aerodynamics and structural dynamics of the FWR wing are strongly coupled, resulting in a complex fluid-structure interaction (FSI) problem. To overcome this challenge, a computational FSI analysis, which couples a computational fluid dynamics (CFD) solver and a computational structural dynamics (CSD) solver, is commonly used to provide detailed information on both flow fields and structural dynamics (Kamakoti & Shyy, 2004; Nakata & Liu, 2012). In this study, we first consider a global point of view in which the effect of dragonfly-like shape on the aerodynamic performance of the FWR model is compared with the baseline rectangular shape by CFD and experimental approaches, also taking aspect ratio into account. We also explore the contribution of the reinforced wingtip and inherent wing elastic deformation to the unsteady aerodynamics and power efficiency of the FWR model through FSI analysis and experiments. Furthermore, we address how wing bending deformation significantly affects aerodynamic performance and propose an optimization and generalizable strategy to achieve efficient biomechanics for FWR-MAV by adjusting the stiffness quantity of the wing along the spanwise direction. Through experimentation and flight tests, the dragonfly-inspired flexible

wings have demonstrated enhanced lift production and power efficiency, effectively supporting the flight capabilities of the FWR model.

5.2 Modelling and Methods

5.2.1 Dragonfly-inspired FWR Wing Model

Several studies of bird and dragonfly wings have revealed that the outer section of the wing has a sweep angle or gradually shrinks along the spanwise direction (Ren et al., 2013; Yang et al., 2019). The shape of the dragonfly forewing and hindwing exhibits a continuous backward curvature of the wingtip at 80%-90% of the span (Bomphrey *et al.*, 2016; Salami *et al.*, 2022). The flexible wing for an FWR-MAV imitates the shape of a dragonfly's hindwing (*Sympetrum sanguineum*) (Bomphrey *et al.*, 2016), as shown in Figure 5-1.

The aspect ratio λ of the wing refers to the ratio of the wingspan R to the root chord length in this study. The dragonfly-like FWR wing shown in Figure 5-1(b) has an aspect ratio of $\lambda = 2.67$. The structure of the FWR wing is composed of a carbon/epoxy frame and polyimide film. The polyimide film has the following material properties: thickness 0.015 mm, density 1.42 g/cm³, and elastic modulus 2.5 GPa. Inspired by the membrane and veins of a dragonfly, which vary along the wingspan and chordwise direction, the thickness e_1 of the leading edge beam (LE-beam) of the FWR wing gradually changes from 3.5 mm at the wing root to 1.5 mm at the wingtip. The chordwise sub-beams choose two carbon fibre rods with diameters $d_1=1$ mm and $d_2=0.6$ mm, respectively.

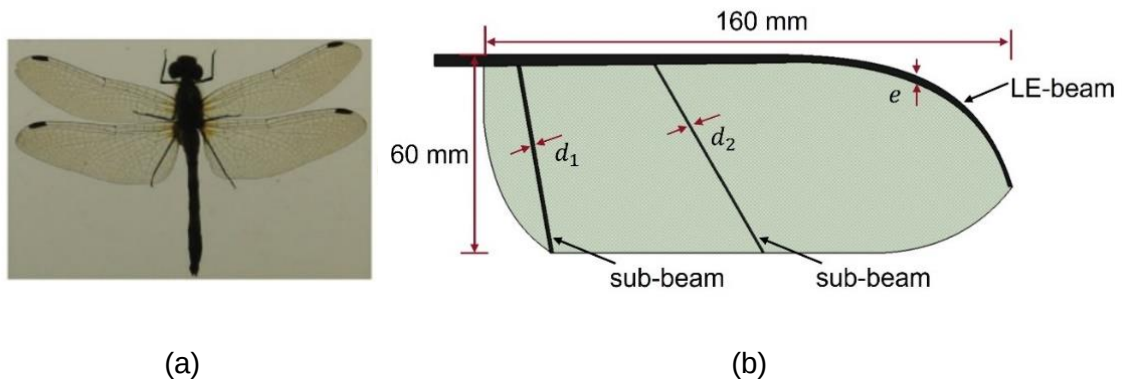


Figure 5-1 (a) Wings of Dragonfly (*Sympetrum sanguineum*) (Bomphrey *et al.*, 2016);(b) Structural layout and dimensions of the dragonfly-like FWR wing.

5.2.2 Wing Kinematic Definition

A flyable FWR-MAV with a pair of dragonfly-like wings is shown in Figure 5-2. The FWR-MAV is driven by a DC motor, performing a vertical flapping motion (ϕ) through a gear-crank transmission mechanism. A sleeve-pin unit is mounted at the free end of the U-shape flapping mechanism that connects to the wing root, allowing the wing to perform a passive pitching motion (α) within a range of angular variation. The flapping wings would produce lift and axially symmetric thrust that would result in a passive rotation motion (ψ).

Figure 5-3(a) shows the coordinate system that can be used to describe the kinematics of the FWR wing. The rigid-body rotations involve four frames: the inertial frame $oxyz$ based on the horizontal plane, two intermediate frames $ox'y'z'$ and $ox''y''z''$, and the wing-fixed frame $ox_wy_wz_w$. The wing would undergo elastic deformation due to the aerodynamic and inertial forces produced by the rigid-body rotations.

For the wing going downstroke at the initial time, the flapping angle is given as

$$\phi = 0.5\Phi\cos(2\pi\hat{t}) \quad (5-1)$$

where Φ is the flapping amplitude; $\hat{t}=ft$ is the dimensionless time ranging from 0 to 1 in a flapping cycle, with the flapping frequency f and physical time t .

When the FWR wing performs passive pitching motion, its angle of attack (AoA) changes abruptly during the flapping stroke reversal, then remains constant for the rest of downstroke and upstroke (Chen et al., 2021). According to the references (Li et al., 2017; Li & Guo, 2018), the pitching angle velocity of the wing in the reversal phase at the end of each stroke can be described as

$$\dot{\alpha} = \frac{2f(\alpha_u - \alpha_d)}{\Delta t_r} \left[(-1)^{(2\hat{t}+0.5)} - \cos\left(\frac{4\pi\hat{t}}{\Delta t_r} - (2\hat{t} - 0.5)\pi\right) \right] \quad (5-2)$$

where Δt_r indicates the dimensionless pitching time with respect to the flapping period.

In this study, the pitching axis of the FWR wing is aligned with the leading edge. The wing has a minimum -10° pitching angle during the flapping downstroke, i.e., $\alpha_d = -10^\circ$, and a maximum 30° pitching angle during the flapping upstroke, i.e., $\alpha_u = 30^\circ$. The flapping motion is sinusoidal and symmetric, ranging from -30° to 30° , as shown in Figure 5-3(b). The rotation speed denoted by n is assumed to remain constant over a flapping cycle.

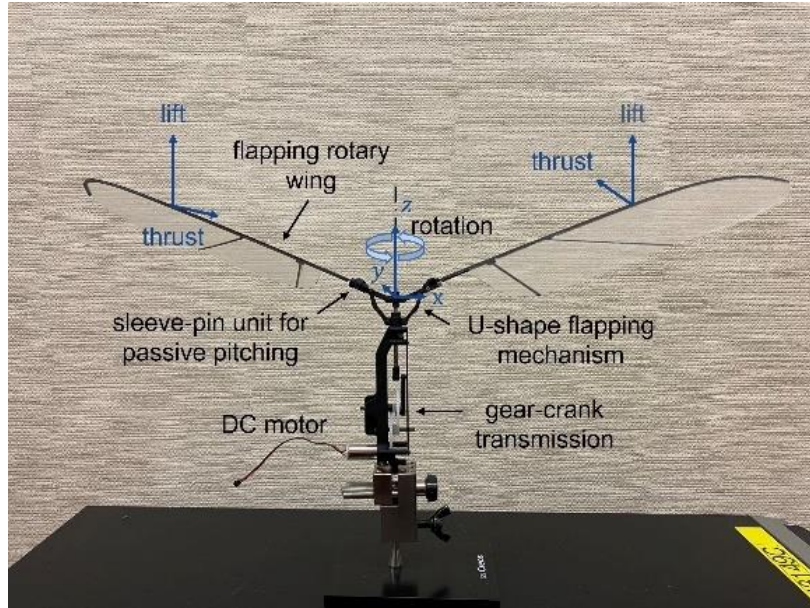


Figure 5-2 A flyable FWR-MAV.

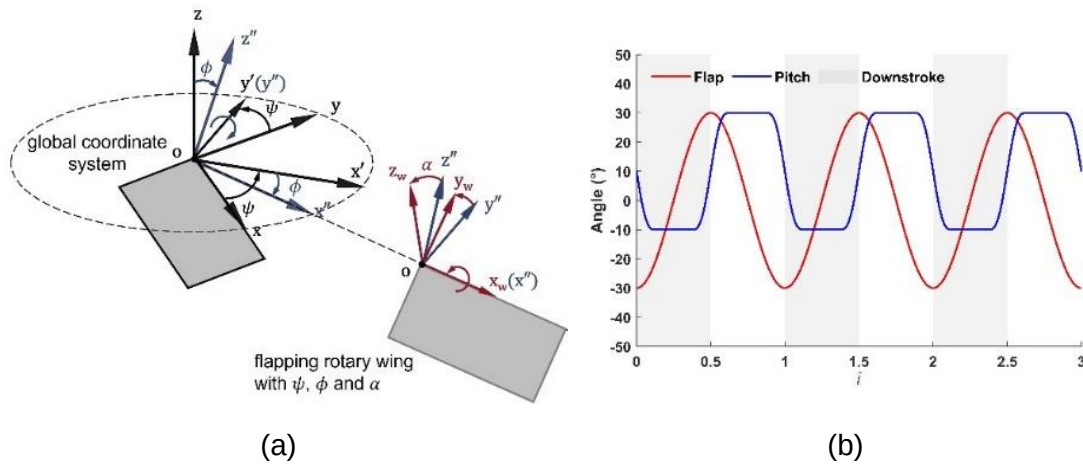


Figure 5-3 (a) Coordinate system definition for the single FWR wing; (b) Time courses of the sinusoidal flapping and passive pitching motions.

5.2.3 Aerodynamic Analysis

The aerodynamic analysis for the whole FWR wing is performed using a computational fluid dynamics (CFD) method, which is governed by the three-dimensional unsteady Navier-Stokes equations. A turbulent model of $k-\omega$ SST is employed in this study. The three-dimensional CFD model, which is a structured and boundary-fitted O-H type mesh, combines a far field, spherical interfaces, and the FWR wing as shown in Figure 5-4. Thus, the fluid field is divided into an outer and an inner fluid field. The inner fluid field follows with the wing rigid rotations by using the dynamic mesh method, and it is compiled with a user-defined functions script. The radius of interior circle is 9.4 times the spanwise length of the wing model to prevent the mesh near the wing coming distorted during the flapping and rotation motions, since it will not be reconstructed during the calculation process. The dimension of the far field cuboid is $20 \times 16 \times 16$ m. The wing is analysed as a rigid body in the CFD simulations.

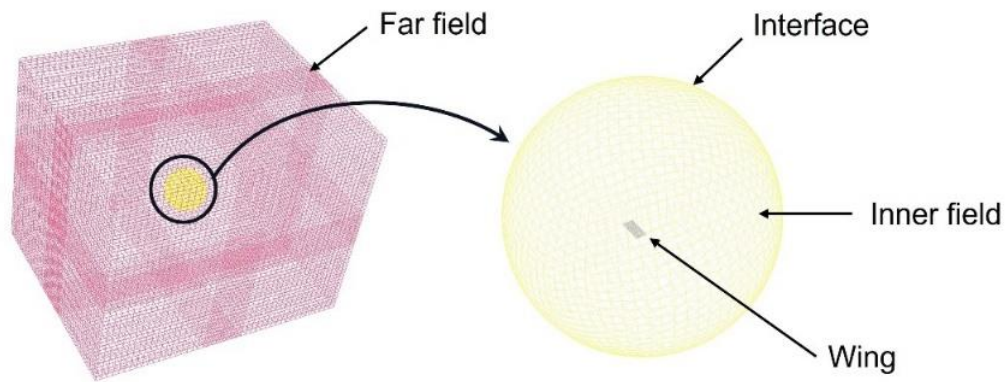


Figure 5-4 Diagram of the CFD model.

In previous CFD study of FWR (Wu et al., 2016), the aerodynamic forces produced by the wing in the inertia coordinate system are obtained by integrating the pressure and velocity components in the flow field around the wing at each physic time. Based on the global coordinate system shown in Figure 5-3(b), the lift, drag, and rotational moment coefficients of the 3D FWR wing obtained from the CFD calculations are defined as follows:

$$C_l = \frac{l}{0.5\rho\bar{U}^2S} \quad (5-3)$$

$$C_d = \frac{d}{0.5\rho\bar{U}^2S}$$

$$C_m = \frac{m}{0.5\rho\bar{U}^2S\bar{c}}$$

where l is the vertical lift force, d is the horizontal drag force, and m is the rotational moment along the z -axis in the inertial system; ρ is the fluid density; S is the wing area; $\bar{c}$ is the mean chord length of the wing. The time averaged values of lift, drag, and moment coefficients are denoted by $\bar{C}_l$, $\bar{C}_d$, and $\bar{C}_m$. The reference velocity $\bar{U}$ is defined by the average flapping velocity at the wingtip, $\bar{U} = 2f\Phi R$, where R is the spanwise length of the wing.

In the previous study (Li & Guo, 2018), the aerodynamic power efficiency of the FWR wing was denoted by a dimensionless power factor P_f that was the ratio of the mean lift coefficient to the mean aerodynamic power efficiency. As the mean aerodynamic power was calculated by the total power required for the wing to produce forces, the aerodynamic power efficiency P_f is determined by the following equation in this study:

$$P_f = \frac{\bar{C}_l}{\bar{C}_l - \bar{C}_d} \quad (5-4)$$

In experiments, the power efficiency of the FWR model S_p is evaluated by the ratio of the average lift force generated by the wings L (N) over a flapping cycle to the power input P (W) from the motor, i.e.,

$$S_p = \frac{L}{P} \quad (5-5)$$

5.2.4 Transient Structural Analysis

The structural dynamic equation of the flexible FWR wing can be derived from Lagrange's equation as follows:

$$\frac{d}{dt} \left(\frac{\partial E_k}{\partial \dot{\mathbf{q}}} \right) - \frac{\partial E_k}{\partial \mathbf{q}} + \frac{\partial E_p}{\partial \mathbf{q}} = \mathbf{Q} \quad (5-6)$$

where E_k and E_p are the wing's kinetic and potential energy, respectively, and $\mathbf{Q}$ denotes the generalized external forces including the drive torque and aerodynamic forces. The generalized coordinate $\mathbf{q}$ that describes the wing kinematics is expressed by,

$$\mathbf{q} = \left[[\mathbf{q}^{rot}]^T, [\mathbf{q}^{ela}_{twist}]^T, [\mathbf{q}^{ela}_{bend}]^T \right]^T \quad (5-7)$$

where $\mathbf{q}^{rot}$ denotes the generalized coordinates of rigid-body rotations referring to rotating, flapping and pitching angles respectively; $\mathbf{q}^{ela}_{twist}$ and $\mathbf{q}^{ela}_{bend}$ represent the generalized coordinates of the wing elastic deformation ($\mathbf{q}^{ela}$) respectively associated to twisting angle (α_{twist}), and bending angle (θ).

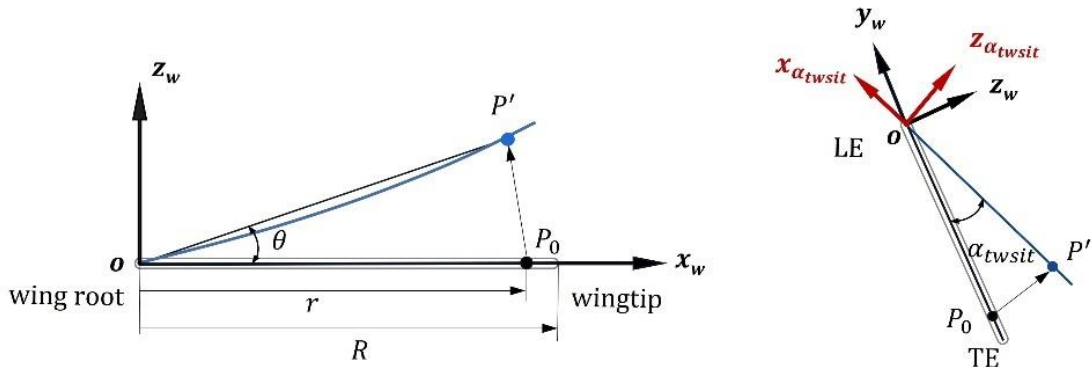


Figure 5-5 2D views of bending and twisting deformations of the flexible FWR wing.

For a general point P_0 on the wing, its position vectors in the inertial frame and the wing-fixed frame are respectively expressed as $\mathbf{r}_i = [x_i y_i z_i]^T$ and $\mathbf{r}_w = [x_w y_w z_w]^T$, as shown in Figure 5-2 and Figure 5-5. The transformation matrix from the wing-fixed frame to the inertial frame is given as $\mathbf{R}_{w \rightarrow i} = \mathbf{R}_\psi \mathbf{R}_\phi \mathbf{R}_\alpha$ (Li et al., 2017). The kinetic energy of the wing is obtained by,

$$E_k = \frac{1}{2} \iint_S e_s \rho \dot{\mathbf{r}}_i^T \dot{\mathbf{r}}_i ds \triangleq \frac{1}{2} \dot{\mathbf{q}}^T \mathbf{M}_w \dot{\mathbf{q}} \quad (5-8)$$

where e_s is the wing skin thickness; s is the area of the undeformed wing; $\mathbf{M}_w$ is the wing's mass matrix.

The potential energy E_p is yielded by the elastic energy storage in the deformations of wing skin and the beams, i.e., $E_p = E_p^{skin} + E_p^{beam}$. The potential energy of wing skin is calculated by the nonlinear strain-displacement relations for plate with a moderate deformation (Wang et al., 2017),

$$E_p^{skin} = \frac{1}{2} \iiint \boldsymbol{\varepsilon}^T \mathbf{C} \boldsymbol{\varepsilon} dv \quad (5-9)$$

where v is the skin volume; $\boldsymbol{\varepsilon}$ is the strain vector of the skin. According to the finite element model, the strain energy for a beam element is given by,

$$(E_p^{beam})_e = \frac{1}{2} (\boldsymbol{\delta}_e)^T \mathbf{K}_e \boldsymbol{\delta}_e \quad (5-10)$$

where $\boldsymbol{\delta}_e$ represents the node displacements; $\mathbf{K}_e$ is the stiffness matrix of the beam element. With the stiffness matrix and the boundary conditions, the overall potential energy of the LE beam E_p^{beam} can be derived.

Therefore, the structural dynamic equation (5-6) can be rewritten in a discrete form based on the Newmark method for transient structural analysis as follow:

$$\mathbf{M}_w \ddot{\mathbf{q}}(t) + (\mathbf{K}_v(t) + \mathbf{K}) \mathbf{q}(t) = \mathbf{Q}_{aero}(t) \quad (5-11)$$

where $\mathbf{K}$ and $\mathbf{K}_v$ are overall static stiffness matrix and dynamic stiffness matrix respectively; $\mathbf{Q}_{aero}$ is composed of aerodynamic forces and the initial forces related to the accelerations of wing motions.

The wing kinematics, including flapping, pitching, and rotation motions introduced in Section 5.2.2, are applied to the wing base as boundary conditions in the transient structural analysis. Therefore, the numerical simulation for FSI is conducted as follows: Initially, the unsteady aerodynamic forces produced by the wing motion at the instant t are computed in CFD. Second, the aerodynamic forces are transferred from the aerodynamic grid to the structural grid, and the displacement of the wing deformation is calculated by solving the structural dynamic equation at the instant t in CSD. After the deformation value converges,

the displacement of the structural grid is then translated to the aerodynamic grid to update the shape of the flexible wing, which returns to the aerodynamic calculation at the next time step, and so on iteratively.

5.2.5 FWR Model Experiment

An experimental platform comprising the devices depicted in Figure 5-6 was constructed to measure the instantaneous force generated by the FWR wings. The FWR model was operated by a DC motor supplied by a DC supply and placed on a load cell (with a capacity of 200 g and an accuracy of 0.05 percent F.S.). The voltage signal acquired from the load cell was transmitted to the data acquisition device through a 1K-gain signal amplifier (NI USB-6009). The data were then transmitted to the LabVIEW programme on the PC to quantify the lift force, filtered using the 2nd-order low-pass Chebyshev filter. The low-pass cut-off frequency was set to five times the flapping frequency (Granlund et al., 2013; Ramesh et al., 2013). This force measurement method was utilised and validated in previous works (Chen et al., 2020; 2021).



Figure 5-6 The experiment setup for force measurement of FWR wings.

5.3 Results and Discussion

5.3.1 Effect of Wingtip Shape

5.3.1.1 Aerodynamic Forces and Power Efficiency

The most remarkable characteristic of a dragonfly's wing is the gradual backward curvature of the LE near the wingtip. We first investigate the aerodynamic forces and power efficiency of the dragonfly-like wings and the baseline rectangular wings with the same aspect ratio. The two types of physical wings installed on the FWR model to be tested are shown in Figure 5-7, and their dimensions and

weights are listed in Table 5-1. The first group is the dragonfly-like wing DW-A and its baseline rectangular wing RW-A with the same aspect ratio of $\lambda = 2.67$. In the second group containing the dragonfly-like wing DW-B and its base wing RW-B, the chord length is extended, and the aspect ratio is $\lambda = 1.78$.

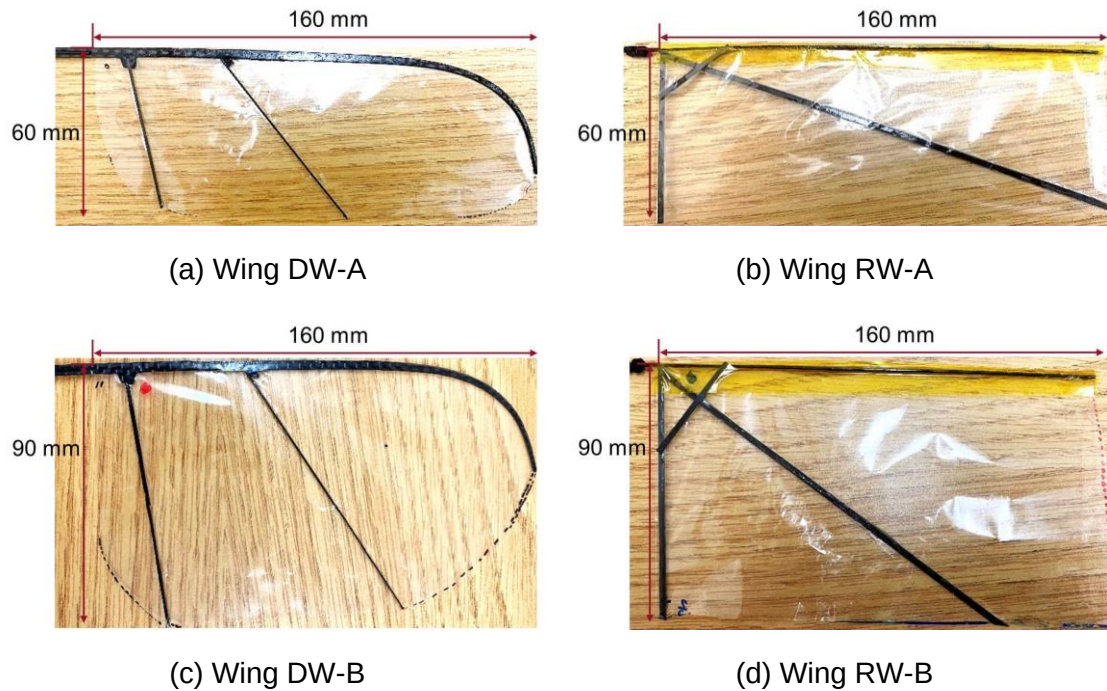


Figure 5-7 Wing Structure and dimensions for the FWR model: (a) Wing DW-A and (b) Wing RW-A ($\lambda = 2.67$); (c) Wing DW-B and (d) Wing RW-B ($\lambda = 1.78$).

Table 5-1 Dimensions and weight of wings.

Wing Name	Wing DW-A	Wing DW-B	Wing RW-A	Wing RW-B
Dimension (mm)	160 × 60	160 × 90	160 × 60	160 × 90
λ	2.67	1.78	2.67	1.78
Weight (g)	1.21	1.35	0.81	0.96

The experimental findings demonstrated that aerodynamic performance was greatly enhanced when the FWR wing adopted the sweep-back shape of the wingtip. In general, for the same input power and flapping frequency, the DW wings consistently produced a higher lift force than their corresponding base wings (Figure 5-8(a)(b)), which can be attributed to a faster rotation speed (Figure

5-8(c)). As the rotation speed of the DW wings rose significantly with flapping frequency to enhance lift generation, the power efficiency of the DW wings generally increased, whereas the power efficiency of the RW wings decreased with increasing flapping frequency (Figure 5-8(d)).

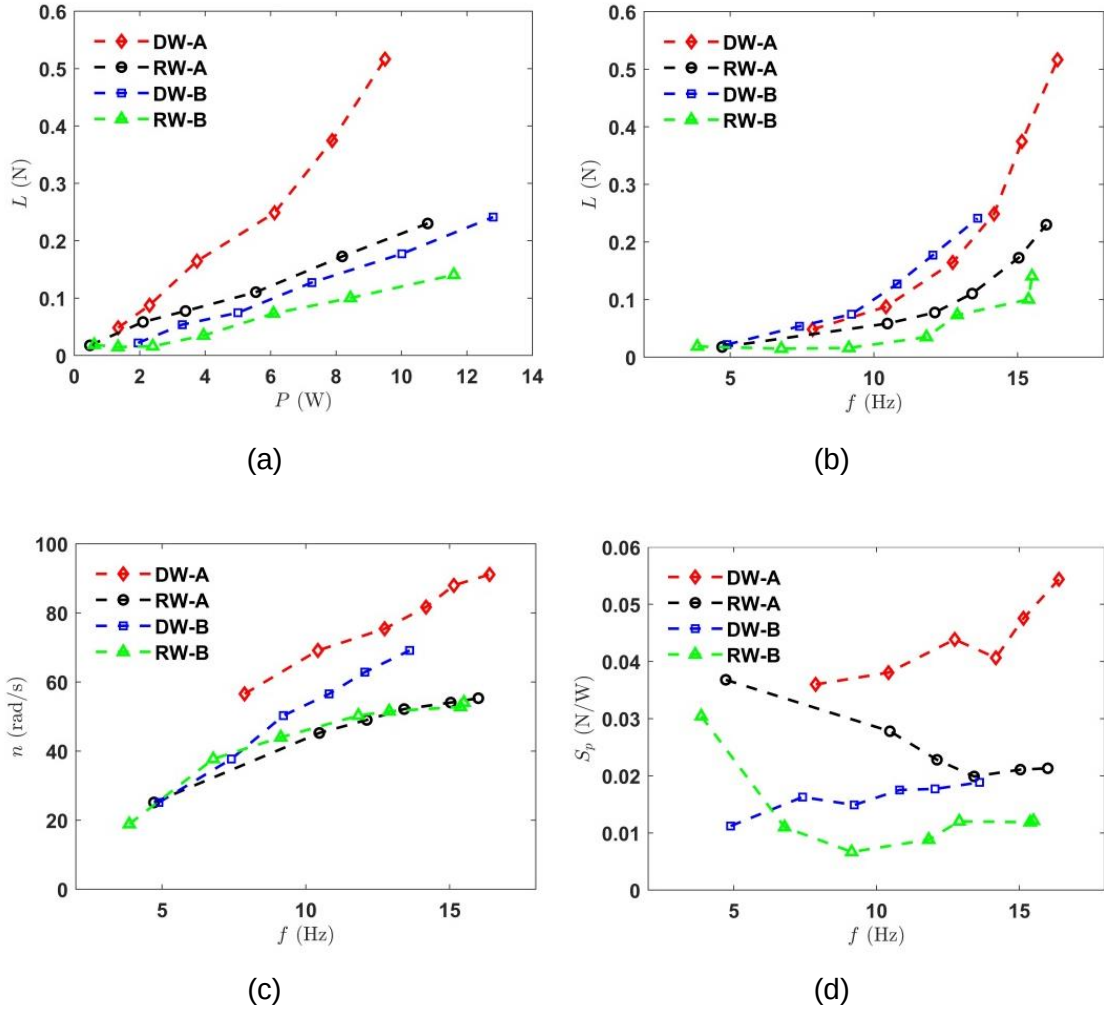


Figure 5-8 The measured average lift force, input power, flapping frequency, rotation speed, and power efficiency of the FWR model with dragonfly-like wings and base wings: (a) the average lift against input power; (b) the average lift against flapping frequency; (c) rotation speed against flapping frequency; (d) power efficiency against flapping frequency.

Specifically, the cases of DW-A and RW-A wings at a frequency of approximately 10.5 Hz are detailed in Table 5-2. For CFD models, mesh sensitivity analysis is conducted by changing the mesh density, with the reducing first grid distance from Mesh 1 to Mesh 2, as shown in Table 5-3. A time step of 0.001 is employed,

and at least five flapping cycles are computed to guarantee result convergence, ensuring consistent average aerodynamic coefficient values across a cycle. The aerodynamic coefficient results of the wings listed in Table 5-3 indicate that the CFD models have converged. Besides, the validation of the CFD simulation is confirmed by comparing the data in Table 5-2 and Table 5-3, which demonstrate minimal variance between the CFD simulation results and experimental measurements: the average lift coefficient from the CFD results show a 4.99% difference compared to the measured value in the Wing DW-A case and a 6.65% difference in the Wing RW-A case.

Table 5-2 Experiment data of Wing DW-A and Wing RW-A.

Model	P (W)	L (N)	S_p (N/W)	f (Hz)	n (rad/s)	$\bar{C}_l$ (test)
Wing DW-A	2.3	0.088	0.038	10.47	69	0.61
Wing RW-A	2.1	0.058	0.028	10.42	45	0.40

Table 5-3 Mesh density and simulation results of the CFD models.

Wing Name	Wing DW-A		Wing RW-A	
Mesh	Mesh 1	Mesh 2	Mesh 1	Mesh 2
Number of nodes	491961	626618	451704	4237301
First grid distance (mm)	0.011	0.009	0.008	0.006
$\bar{C}_l$	0.580	0.576	0.430	0.428
$\bar{C}_d$	-0.222	-0.215	-0.095	-0.092

In the above results, using the Wing DW-A can increase the average lift by 50% and power by 36% when compared to the Wing RW-A. Furthermore, the faster rotational speed of Wing DW-A compared to Wing RW-A corresponds to an increase in the incoming flow velocity. Thus, the aerodynamic forces produced increase, and the effective angle of attack shifts. This is highlighted more prominently in the instantaneous results of the CFD, as shown in Figure 5-9, where the peak positive lift generated during the downstroke of Wing DW-A

increases and the negative lift during the upstroke decreases. The peak rotation moment during the downstroke also increases significantly. The average rotation moment coefficients of Wing DW-A and Wing RW-A are 0.062 and 0.058, respectively. This indicates that the consistency between experimental and simulated data enables the use of numerical simulations for later analysing wing fluid structure evolution, thereby aiding in addressing the wings FSI problem.

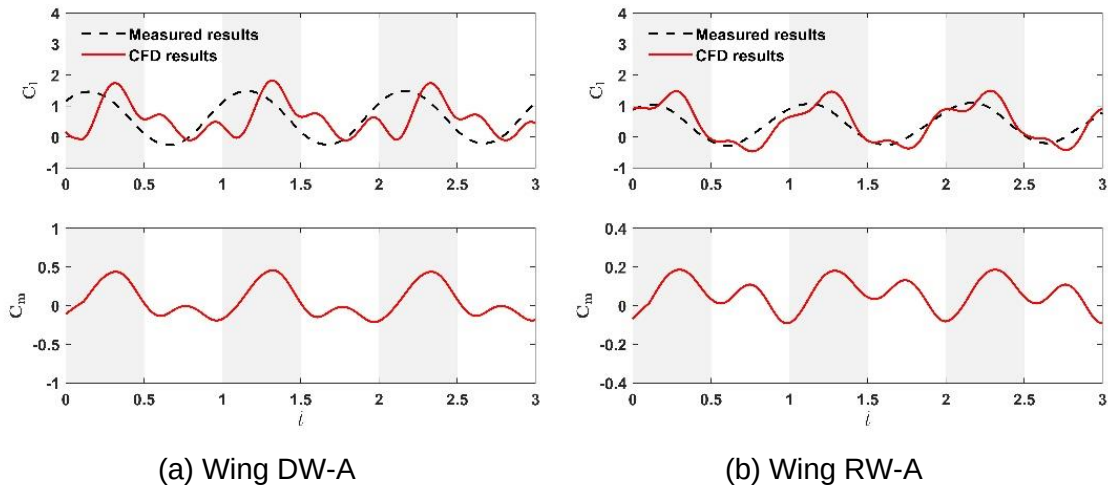


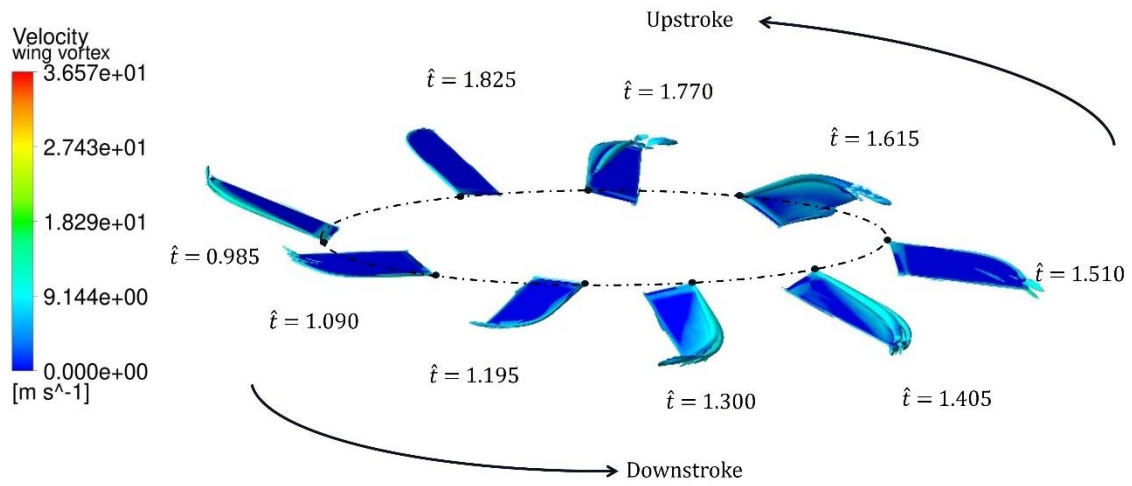
Figure 5-9 Time course of lift and moment coefficients of (a) Wing DW-A and (b) Wing RW-A.

5.3.1.2 Flow Analysis

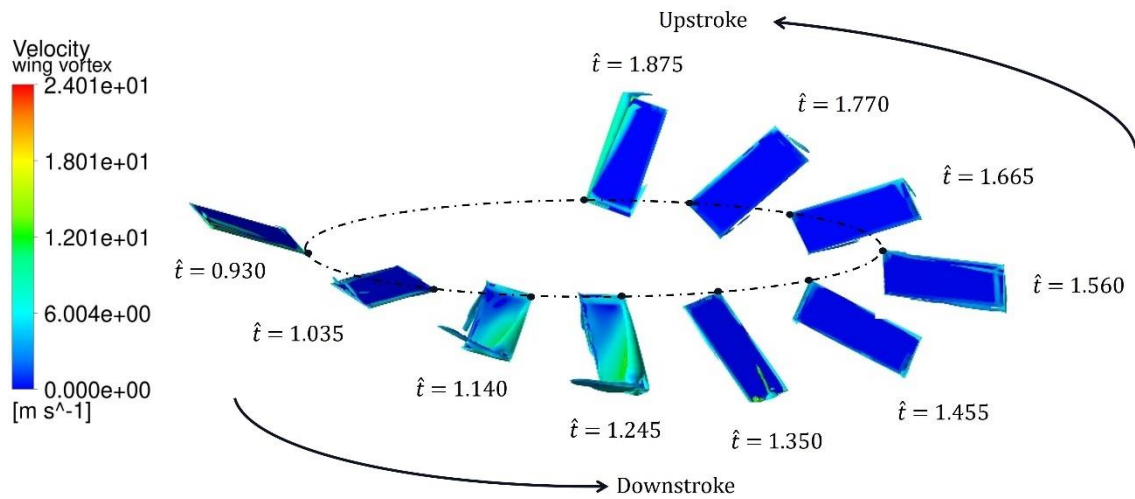
The shape of the wing has a direct effect on the flow around the wing, i.e., the aerodynamic mechanism of the FWR wing, which consists of an attached leading edge vortex (LEV), added mass, wake capture, and rotational circulation. Given that the quasi-steady model utilized in previous investigations does not incorporate the effects of spanwise flow and wingtip vortex, the CFD method is a suitable and precise method for elucidating the aerodynamic mechanism of dragonfly-like FWR wings through the visualization of flow fields around the wing.

The LEV has been identified as a major contributing factor to the high lift production for the insect flights (Ellington et al., 1996; Lua et al., 2016; Wang et al., 2004). The DW wing can generate high lift and have great aerodynamic efficiency, which is precisely because the LEV develops and extends along the curvature of the LE-beam and remains stably attached to the wing surface. This

can be obviously seen in Figure 5-10: when the spanwise velocity along the LEV core transports vorticity towards the wingtip, the wingtip curvature of Wing DW-A allows the vorticity to smoothly extend to the trailing edge, resulting in a vortex ring connecting the leading edge and trailing edge (at $\hat{t} = 1.3$ in Figure 5-10(a)). In contrast, the spanwise LEV of Wing RW-A sheds at the wingtip (at $\hat{t} = 1.245$ in Figure 5-10(b)). Moreover, the greatest LEV development occurs on Wing DW-A when the lift coefficient reaches its maximum value at $\hat{t} = 1.3$, and the vortex formation is later than on Wing RW-A. For Wing RW-A, the vortex forms best at $\hat{t} = 1.245$. The maximum vortex formation of Wing DW-A is also delayed in terms of the peak value of flapping velocity emerging at $\hat{t} = 1.25$, which is beneficial for enhancing lift production. Therefore, this sweep-back wingtip shape makes effective use of the stable attachment of the LEV and delayed stall mechanism.



(a) Wing DW-A



(b) Wing RW-A

Figure 5-10 Wing vorticity distribution of 10.5 Hz flapping examples with colour indication of velocity variation over a flapping cycle: (a) Wing DW-A and (b) Wing RW-A.

5.3.2 Effect of Aspect Ratio

Figure 5-8 presents the experimental results of DW and RW wings, which demonstrate the effect of aspect ratio on aerodynamic forces and power efficiency. Specifically, when comparing Wing DW-A ($\lambda = 2.67$) and Wing DW-B ($\lambda = 1.78$) at the same flapping frequency, the fast rotation speed of Wing DW-A compared to Wing DW-B with a small aspect ratio indicates higher thrust but lower lift generation. As the trust increased, the required power is reduced. In other words, at the same input power, Wing DW-A rotates faster and generates significantly more lift than Wing DW-B. Consequently, the power efficiency of Wing DW-A is higher than that of Wing DW-B.

Similar conclusions are drawn when comparing their rectangular baselines, Wing RW-A ($\lambda = 2.67$) and Wing RW-B ($\lambda = 1.78$), indicating that decreasing aspect ratio increases the wing's area and weight, leading to changes in passive pitching motion due to inertial forces and altering the direction of the effective angle of attack, resulting in decreased lift and increased thrust. Overall, the power efficiency deteriorates.

5.3.3 Effect of Wingtip Chordwise Stiffness

5.3.3.1 Aerodynamic Forces and Power Efficiency

The above Section 5.3.1 demonstrates that DW wings can generate greater lift than RW wings. This is not only due to the aerodynamic changes caused by the shape but also due to the factor of reinforced wingtip stiffness. The LE-beam of the DW wing encloses the wingtip, enhancing its chordwise stiffness. To analyse and verify the effect of this chordwise strengthening structure, a sub-beam was added at the wingtip of Wing RW-A, as shown in Figure 5-11. Wing RW-A is compared with the reinforced Wing RW-C under the same shape conditions.



Figure 5-11 Structure and dimensions of Wing RW-C.

Table 5-4 Dimensions and weight of Wing RW-C.

Parameters	Wing RW-C
Dimension (mm)	160 × 60
λ	2.67
Weight (g)	0.85

The measured results of Wing RW-C in comparison to Wing RW-A are shown in Figure 5-12. When compared under the same input power or frequency conditions, the reinforced Wing RW-C has greater lift than the original Wing RW-A (Figure 5-12(a)(b)). The two wings have approximately the same rotational speed at the same flapping frequency (Figure 5-12(c)). It can be inferred from the curves plotted in Figure 5-12 that when the FWR model with Wing RW-C flaps at a frequency of 10.5 Hz, it generates a total average lift of 0.09 N, which is 1.55 times higher than that generated by Wing RW-A. Moreover, its input power is 2.9 W, and its power efficiency is 0.031 N/W, which is 1.11 times that of Wing RW-A (Figure 5-12(d)). The above results imply that the presence of a reinforced wingtip in the FWR wing has a positive impact on lift generation enhancement, as opposed to thrust, at the specified flapping frequency.

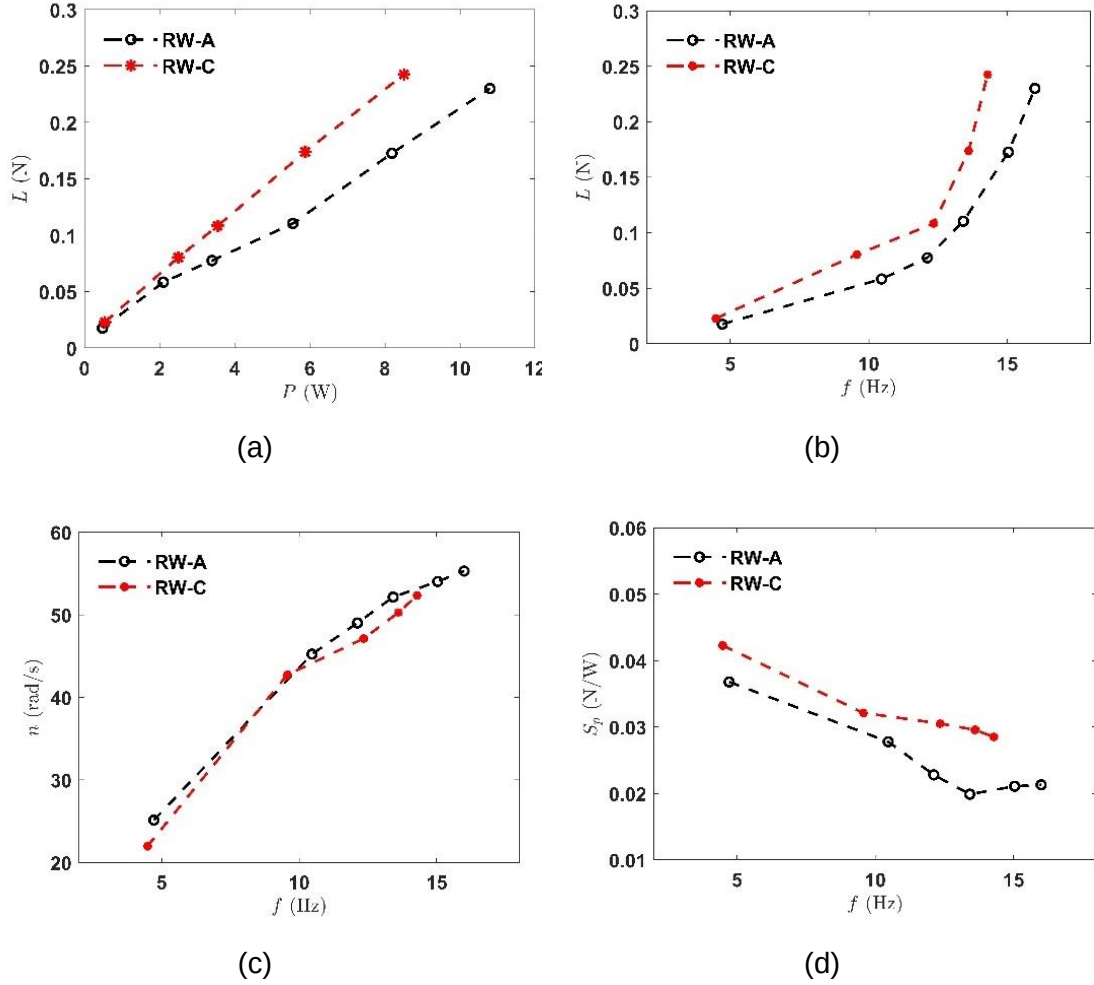


Figure 5-12 The measured results of the FWR model with Wing RW-C compared with Wing RW-A: (a) the average lift against input power; (b) the average lift against flapping frequency; (c) rotation speed against flapping frequency; (d) power efficiency against flapping frequency.

5.3.3.2 Dynamic Responses

The reinforcement of the wingtip affects the deformation of the flexible wings in terms of twist and bend, which has a positive impact on lift production. Figure 5-13 shows the lift and moment coefficients, along with elastic deformation at the wing root and wingtip, of Wing RW-A and Wing RW-C flapping at 10.5 Hz with a rotation speed of 45 rad/s. The twisting angle of Wing RW-C is greater than that of Wing RW-A due to the former's mass lump at the wing tip, which results in a higher passive twisting moment around the spanwise axis of the LE-beam. The centre of mass of Wing RW-C in the chordwise direction is located at $0.37 \bar{c}$, while

that of Wing RW-A is located at $0.34 \bar{c}$, contributing to the difference in twisting angle. Moreover, the wingtip stiffness of Wing RW-C leads to a smaller peak twisting deformation at the wingtip compared to that at the wing root, which is not observed in Wing RW-A. The mass lump also increases the spanwise bending of Wing RW-C, causing higher lift and rotation coefficients with $\bar{C}_l = 0.74$ and $\bar{C}_m = 0.048$ at larger flapping and pitching angles, while the flexible Wing RW-A model has lower values of $\bar{C}_l = 0.45$ and $\bar{C}_m = -0.024$, requiring more power. The above results indicate that the wing inertia plays a significant role in wing deformation and aerodynamic performance.

Figure 5-14 further reveals that the initial stages of the downstroke and upstroke result in rapid pitching and flapping variations in the flexible wing. During the initial state ($\hat{t}$ from 1.02 to 1.20), upward bending deformation allows Wing RWC to exhibit large flapping angles with a peak value of lift (seen in Figure 5-13(b)). The wing experiences serious deformations during the period between the end of the downstroke and the beginning of the upstroke ($\hat{t}$ from 1.43 to 1.65), including reverse flapping and pitching angles. This induces a delayed pitching angle variation at the wingtip compared to the wing root and rigid model, ultimately reducing thrust production.

Prior research of a pitching-flapping-perturbed revolving wing suggests that advanced pitching can enhance the reduction of external driving torque, while delayed pitching can decrease both the driving torque and lift production (Chen et al., 2018). Indeed, in flapping studies, it has been observed that rapid pitch rotation about the spanwise axis before the end of the stroke can enhance lift, whereas delaying pitch rotation after reaching the end of the stroke results in a decrease in lift (Dickinson et al., 1999; Sane & Dickinson, 2002). Despite the decrease in thrust production caused by the elastic deformation of the wing during this flapping reversed period, the upward bending deformation during the upstroke can maintain lift generation. This demonstrates the significance of bending deformation in affecting the aerodynamic performance of the flexible wing.

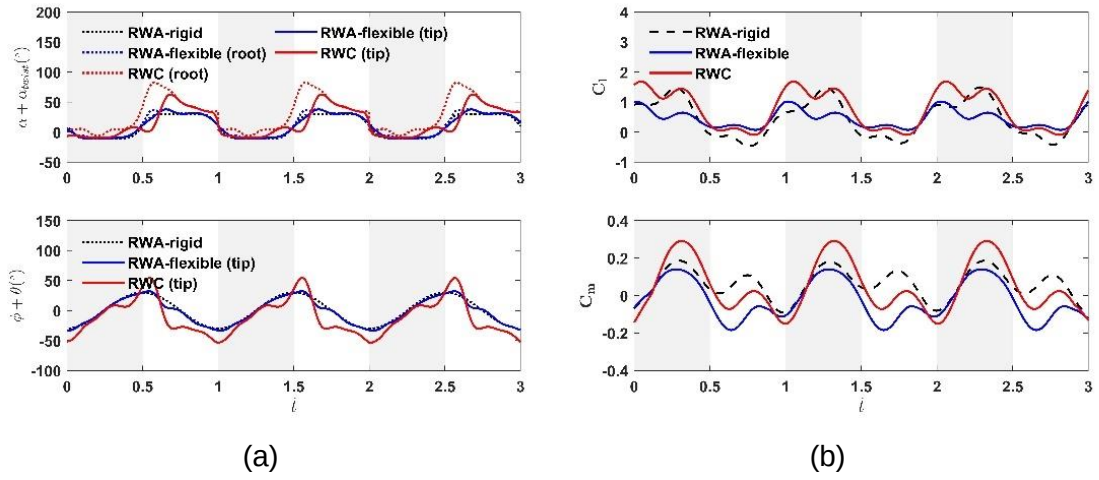


Figure 5-13 Wing deflections and aerodynamic forces of Wing RW-A and reinforced Wing RW-C under aerodynamic and structural coupling: (a) pitching and twisting angles of wing root and tip, flapping and bending angles of wing tip at LE beam; (b) time courses of lift and moment coefficients.

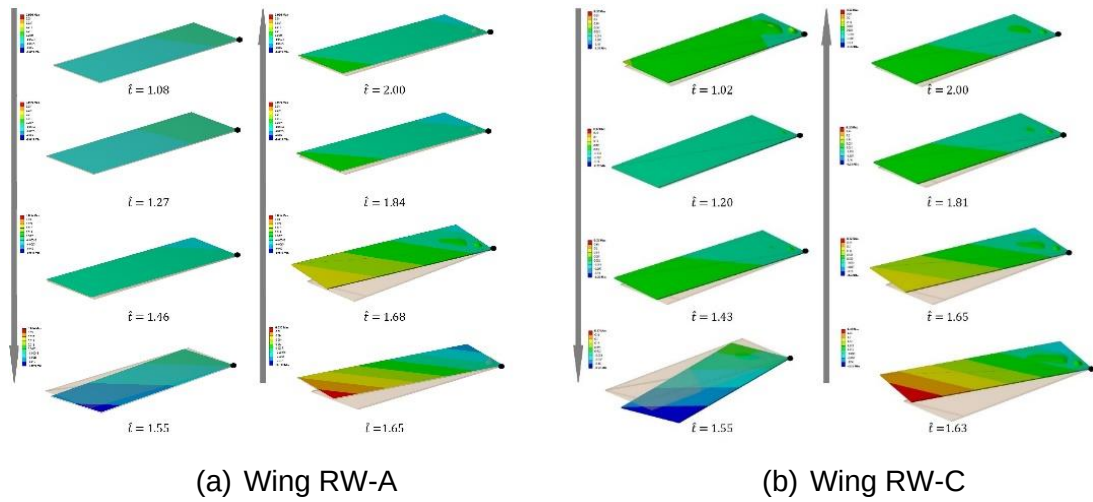


Figure 5-14 Transient deformations in z-direction of flexible (a) Wing RW-A and (b) Wing RW-C.

5.3.4 Effect of Spanwise Deformation and Stiffness

The thickness variation in dragonfly wings is a result of venation, where veins surround the membrane and gradually decrease in thickness from the wing root to the wing tip. This allows dragonflies to maintain unsteady flight with high efficiency. Therefore, the spanwise stiffness of the wings is particularly important for effectively controlling wing deformation during flapping. This study focuses on

investigating the mechanism by which spanwise deformation of the wings affects aerodynamic forces of FWR, with the aim of optimizing the use of flexible wings by employing strategies inspired by the spanwise stiffness variation in dragonfly wings.

5.3.4.1 Aerodynamic Mechanism of Wing Spanwise Deformation

Similar to the advanced pitching rotation, it can be inferred that delaying the acceleration of flapping at the beginning or end of the stroke can improve lift and thrust generation. As demonstrated in Section 5.3.3.2 above, during the initial state of flapping downstroke and upstroke, a flexible wing undergoes a bending deformation, causing it to lag behind the rigid rotation during the stroke. Hence, the effect of spanwise deformation on the aerodynamics of the flexible wing can be considered as an effect of the delayed vortex formation resulting from the corresponding delay in flapping motion.

The flapping delay process is modelled as a time interval during which the flapping wing maintains a constant flapping angle at the beginning of the downstroke and upstroke. This time interval is denoted by a dimensionless flapping delay time (t_n), and its value divided by the flapping frequency yields the physical time of flapping delay. In this study, the wing motion is simulated using flapping amplitudes of 70° , pitching amplitudes of 40° , and a rotation speed of 8.2 rad/s, as shown in Figure 5-15(a). At a flapping frequency of 10 Hz, different flapping delay time (t_n) cases are considered. The $t_n = 0$ case represents non-delayed flapping with rigid rotation. Increasing t_n causes a backward delay in the occurrence of the peak of acceleration, as shown in Figure 5-15(b).

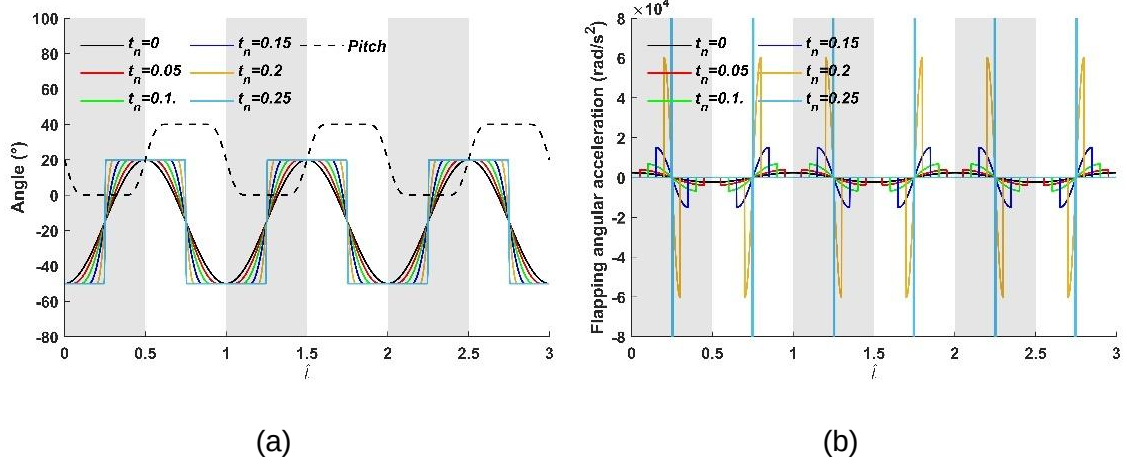


Figure 5-15 Wing kinematics under different flapping delay times: (a) flapping and pitching angle variations and (b) flapping angular acceleration.



Figure 5-16 The simplified wing model of Wing DW-A.

To streamline the calculations, a simplified rigid wing model based on the shape of the Wing DW-A was employed for CFD simulations, as depicted in Figure 5-16. This model exhibits consistent flow characteristics with the Wing DW-A. The sweep-back wingtip shape can promote the extension of the LEV and the formation of a vortex ring attached to the wing surface, which is conducive to high lift production, as shown in Figure 5-17. It is also demonstrated that delayed flapping motion affects vortex formation during the downstroke. The formation of vortices in cases $t_n = 0.1$ and $t_n = 0.2$ occurs at $\hat{t} = 0.2$ and $\hat{t} = 0.3$ respectively, corresponding to the wing's downward motion with a high flapping velocity. The maximum lift generated occurs when a stable and complete vortex ring attaches to the wing surface. However, for $t_n = 0.25$, the extremely rapid flapping rotation at the end of stroke, coupled with poor synchronization between

flapping and pitching motions, results in the vortex detaching from the wing surface during the flapping cycle, leading to undesirable aerodynamic performance. Further details on the aerodynamic forces are presented in the following Figure 5-18.

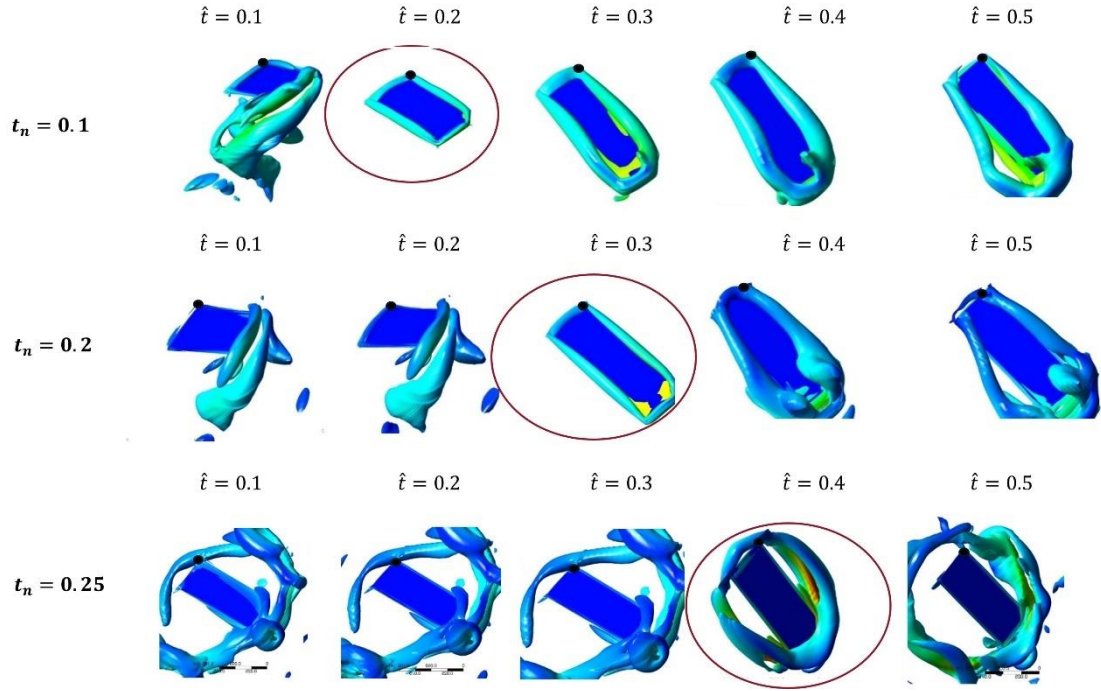


Figure 5-17 Vorticity variation of the wing model during the downstroke in different delayed flapping cases at a flapping frequency of 10 Hz.

Figure 5-18(a) shows the instantaneous lift coefficient of the wing model at 10 Hz with the same delay flapping t_n from the wing root to the wing tip. The peak of lift coefficient increases significantly around the mid-stroke with an increase of t_n from 0 to 0.25, owing to the corresponding increase in flapping velocity and acceleration. Therefore, the wing model benefits from delayed flapping time, exhibiting a higher mean lift coefficient than the non-delayed case $t_n = 0$. Figure 5-18(b) reveals that the maximum lift coefficient generated by delayed flapping $t_n = 0.2$ increases by 71%, 69%, 91%, and 96% at 5 Hz, 10 Hz, 15 Hz, and 20 Hz, respectively, compared to the non-delayed case. However, when the flapping motion is significantly delayed to $t_n = 0.25$, the lift coefficient experiences a sharp decline due to the negative lift force generated during the upstroke.

The effect of delayed flapping on thrust (negative drag) is shown in Figure 5-18(c), where a decrease followed by a gradual increase in thrust is observed at low frequencies of 5 Hz and 10 Hz. During this frequency range, high lift production leads to a corresponding increase in aerodynamic power efficiency P_f , as demonstrated in Figure 5-18(d), compared to the non-delayed case. In contrast, thrust continues to increase with the flapping frequency beyond 15 Hz. However, when the delayed time t_n exceeds 0.2, although thrust reaches high values, the aerodynamic power efficiency drops dramatically below zero due to the negative average lift. Overall, the above results indicate that the wing loses its function if it is too flexible to cause a large delay in flapping, i.e., $t_n > 0.2$.

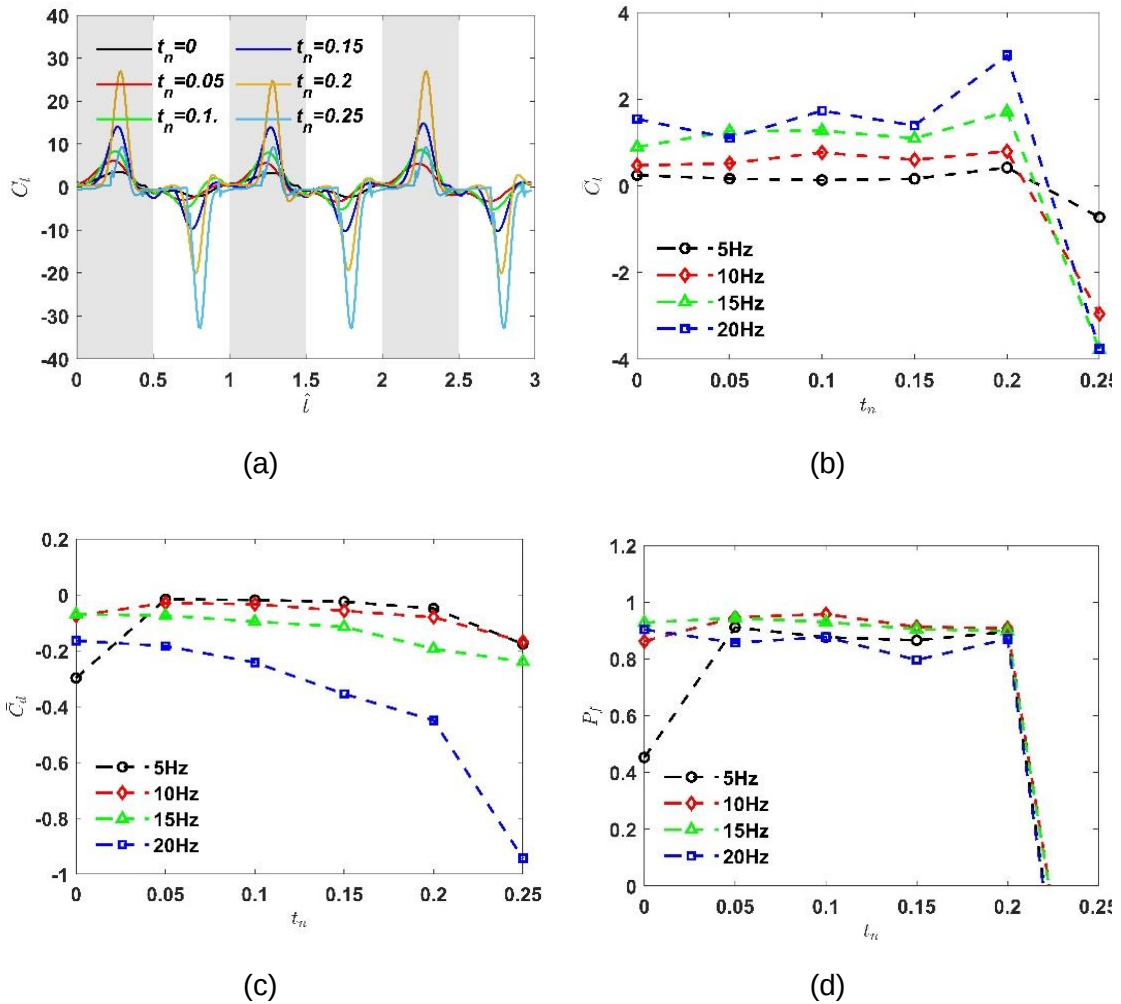


Figure 5-18 (a) Time course of lift coefficient of the wing model at the flapping frequency of 10 Hz; Variations of (b) the mean lift coefficient, (c) the mean thrust coefficient, and

(d) the aerodynamic power efficiency (d) against the different flapping delay times at the flapping frequencies of 5 Hz, 10 Hz, 15 Hz, and 20 Hz.

5.3.4.2 Effect of Wing Flexibility

According to the foregoing analysis, the spanwise deformation of the flapping wing affects the aerodynamic forces through the vortex delay mechanism. The wing deformation can be modelled as the bending of a cantilever beam, with varying flapping delay time t_n along the spanwise direction. The nodes along the spanwise direction are denoted by r , with t_n increasing gradually from the wing root to the wing tip, as tabulated in Table 5-5. The flexible wing cases FW-A to FW-E represent the wing's flexibility from stiff to flexible, with the wing model without delayed flapping serving as the rigid baseline in this analysis. A node represents a chordwise wing strip, and the segment's aerodynamic forces are determined by the wing's rotational speed at that location and the corresponding aerodynamic coefficients obtained for each delayed flapping time in the condition of all the nodes with the same delay. These forces are then integrated along the entire wing to obtain the total force.

The aerodynamic performance of different flexible wing models, namely FW-A to FW-E, is presented in Figure 5-19. Except for the FW-E, which has the greatest flexibility in deforming from the wing root, all other wings can achieve better aerodynamic performance than the rigid baseline wing.

The relationship between wing flexibility and aerodynamic performance with respect to flapping frequency is noteworthy. Among the tested wing models, FW-D exhibits the highest lift performance, with a lift enhancement of 58% to 68% compared to the rigid wing when flapping at a frequency between 10 Hz and 20 Hz. However, its power efficiency diminishes and becomes lower than the rigid wing after 15 Hz. FW-C also exhibits lower power efficiency than that of the rigid wing at 15 Hz. In contrast, FW-B increases the lift produced by a rigid wing by 38% to 47% at a frequency range between 10 Hz and 20 Hz while maintaining the maximum power efficiency at 10 Hz and keeping it higher than the rigid wing as the flapping frequency increases to 15 Hz. Therefore, the deformation pattern of FW-B is highly suitable for the FWR at a wide range of flapping frequencies.

Table 5-5 Cases for modelling the FWR wing with flexibility along the spanwise.

Cases	Node (r/R)	0	0.2	0.4	0.6	0.8	1	Flexibility
FW-A	t_d	0	0	0	0	0	0.05	stiff
FW-B	t_d	0	0	0	0	0.05	0.1	↓
FW-C	t_d	0	0	0	0.05	0.1	0.15	
FW-D	t_d	0	0	0.05	0.1	0.15	0.2	
FW-E	t_d	0	0.05	0.1	0.15	0.2	0.25	flexible

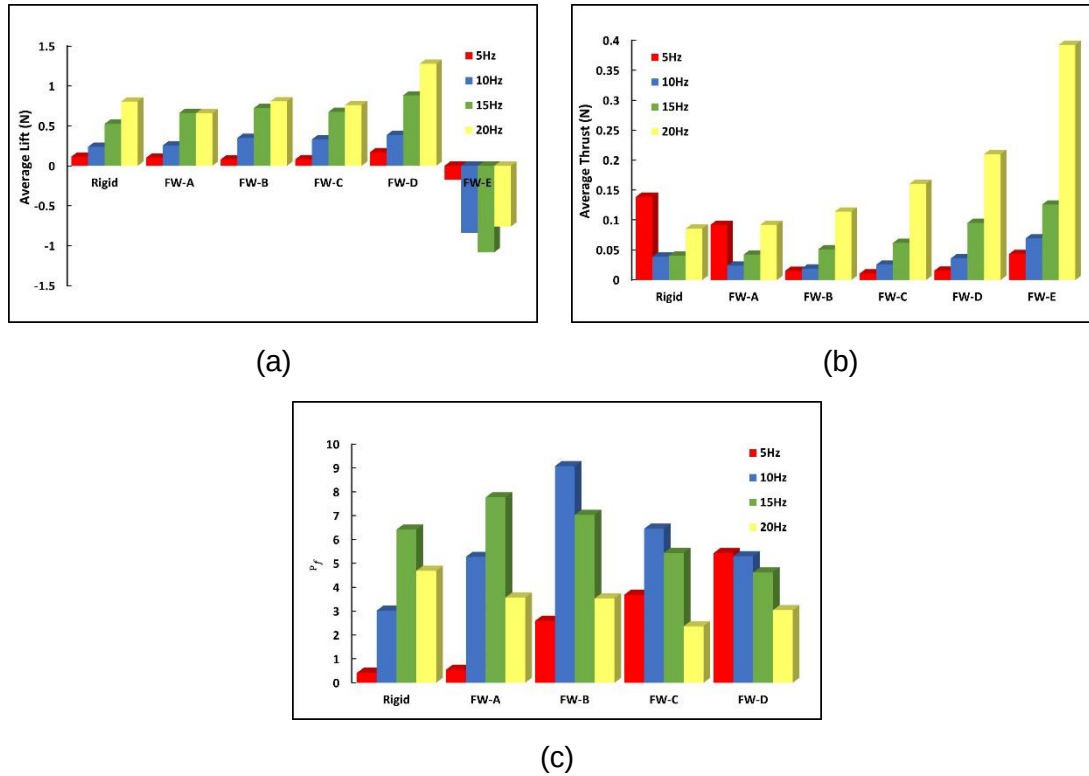


Figure 5-19 (a) Average lift, (b) average thrust, and (c) power efficiency of the modelled flexible wing (from FW-A to FW-E) in a flapping cycle.

5.3.4.3 Variable Spanwise Stiffness

By disregarding the twisting deformation, the deflection of the wing in the spanwise direction is calculated through the utilization of the cantilever beam equation, expressed as follows:

$$EI \cdot z_w(r) = \int_{r=0}^R \left[\int_{r=0}^R -M_y(r) dr \right] dr \quad (5-12)$$

where the vertical deflection $z_w(r)$ is determined based on the reference flapping velocity at r and the physical delayed time (t_n/f), i.e., $z_w(r) = U_{ref}(r) \cdot t_n/f$; EI indicates the spanwise stiffness of the flexible wing model; the bending moment endured by the wing M_y is computed by integrating the sectional lift force along the span.

The EI of a physical FWR wing is measured by placing a lumped mass on the LE-beam along various spanwise positions (LP1 to LP5), as shown in Figure 5-20. By measuring the vertical displacement of the wing at each loading point and applying the cantilever beam deflection equation (5-12), the EI of the wing cross-section is determined.

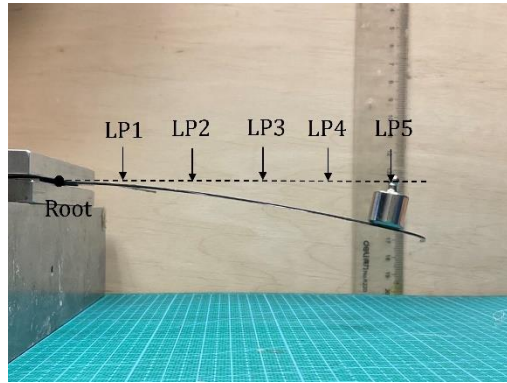


Figure 5-20 Schematic of wingspan stiffness static measurement.

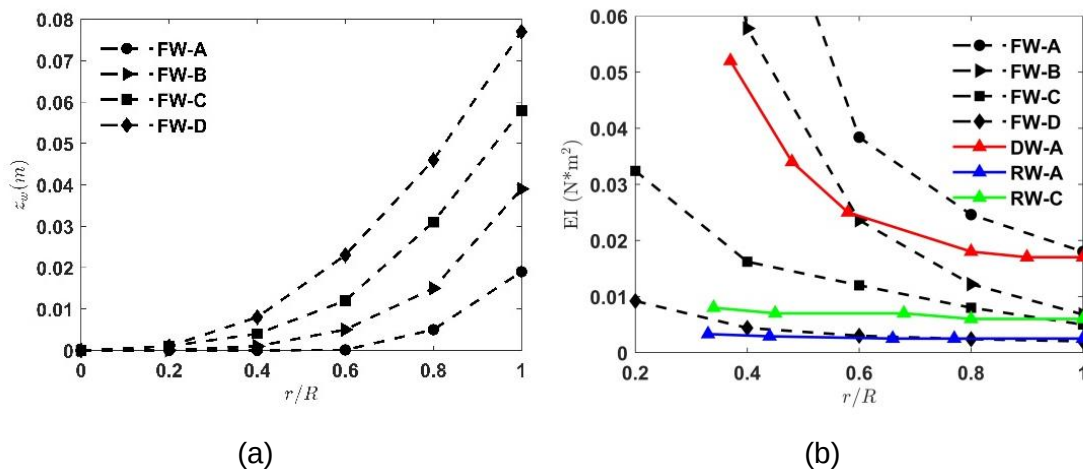


Figure 5-21 (a) Average deflection over a flapping cycle along the wingspan and (b) comparison of the equivalent stiffness of flexible wing models (FW-A to FW-D) and the measured stiffness of the wing test models (DW-A, RW-A and RW-C).

Figure 5-21(a) illustrates that under the 10 Hz flapping motion condition, the most flexible FW-D model requires a significant deflection of the wingtip with a flapping delay of $t_n = 0.2$, resulting in a wingtip deflection of 0.077 m. On the other hand, the relatively rigid FWA exhibits the smallest deflection with a flapping delay of $t_n = 0.05$, resulting in a wingtip deflection of only 0.019 m. The EI values obtained from these deflection calculations are compared with the measured stiffness of the flexible wing test models (DW-A, RW-A, and RW-C) in Figure 5-21(b).

The baseline Wing RW-A has the smallest stiffness among the test models, exceeding that of the modelled FW-D. As a result, the delayed mechanism cannot be fully utilized, leading to poor aerodynamic efficiency. After wingtip reinforcement, the spanwise stiffness of Wing RW-C is between FW-C and FW-D, resulting in improved lift and power efficiency. In contrast, the stiffness of DW-A varies along the spanwise direction in a pattern between FW-B and FW-A, exhibiting significant delayed vortex generation effects, hence it exhibits the highest aerodynamic efficiency.

These results indicate that wing flexibility is not necessarily better, as excessive flexibility can lead to increased elastic deformation, impeding vortex formation and stability, and decreasing aerodynamic efficiency. Within the range of stiffness evaluated in this study, i.e., from FW-A to FW-D, moderate flexibility with spanwise stiffness variation resulting in elastic deformation that delays wing flapping motion from the wing's middle to the wingtip (flapping delay of $t_n=0.1$) can achieve the greatest aerodynamic efficiency for flexible wings. Additionally, the dragonfly-like wing model presented in this study can be easily constructed by adjusting the thickness of the curving LE-beam, enabling the FWR-MAV to obtain aerodynamic benefits from a flexible structure.

5.3.5 Flight Test of the FWR With Dragonfly-like Wings

The FWR model (Figure 5-2) is driven by a DC motor with a total weight of 25 g, including a 3.7 V lithium battery and flight control board. Experimental measurements in Figure 5-9 demonstrated that with a 3.5 V DC supply input, the FWR model using dragonfly-like wings (Wing DW-A) generated sufficient lift (38 g at 7.88 W) to overcome the model's weight, while the rectangular wing model (Wing RW-A) produced only 17.6 g (8.2 W) of lift. Consequently, the FWR model equipped with Wing DW-A successfully achieved take-off and hovering in both indoor and outdoor tests by remote control, as illustrated in Figure 5-22(a)(b)(c). Apart from the motor, the onboard devices of the FWR model during flight tests consist solely of a 3.7 V 58 mAh Li-Po battery and a 2.4 GHz radio receiver, which together weight 2 g, sourced from a commercial micro bionic bird MetaFly. The radio transmitter adjusts only the thruster, altering the motor input power to change the flapping frequency, thus demonstrating the FWR model's self-stabilization capability during free flights without an onboard attitude control unit.

Furthermore, owing to the high lift production and power efficiency of dragonfly-like wings, an FWR model, employing the same pair of wings and driven by two cooperating motors, increased the take-off weight to 51 g and successfully completed flights, as shown in Figure 5-22(d). In contrast, most conventional insect-like two-wing tailless flyable flapping wing MAVs typically necessitate an increased wingspan to produce sufficient lift for flight, even when using a dual-motor configuration. For example, regarding single motor configurations, the 19 g Nano Hummingbird (Keennon *et al.*, 2012) has a wingspan of 165 mm, while the 22 g Colibri (Roshanbin *et al.*, 2017) spans 210 mm. The dual-motor butterfly-type ornithopter has a weight of 38.6 g and extends the wingspan to 648 mm (Leys *et al.*, 2015). In future research, the flight control system, encompassing attitude mechanisms, will be explored to achieve stable VTOL, hovering, and forward flights for practical FWR-MAV applications.

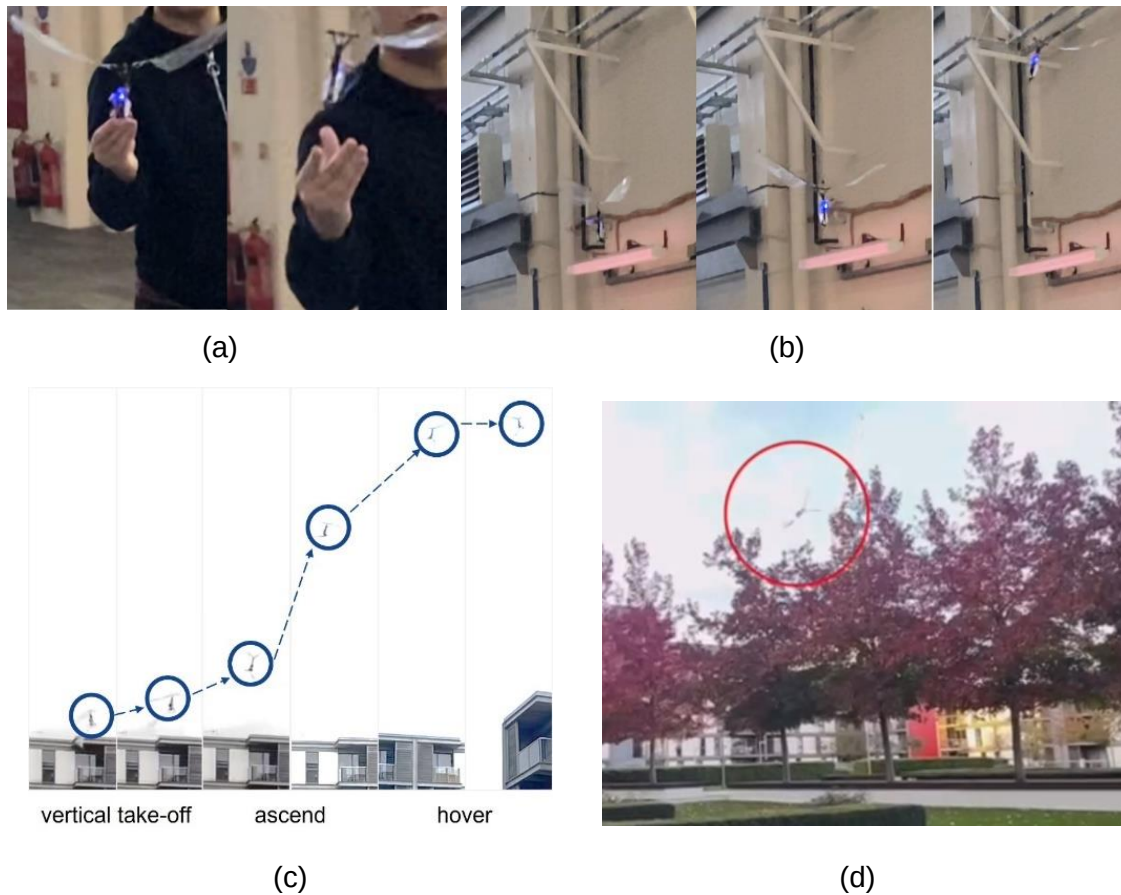


Figure 5-22 Single-Motor FWR model with dragonfly-like wings: (a) hand launch, (b) indoor vertical take-off, (c) outdoor flight test; (d) Dual-motor FWR model flight test using the same wings.

5.4 Conclusion

This study examined the aerodynamic performance of a flexible wing for flapping-wing micro air vehicles, focusing on a dragonfly-like wing design with a sweep-back wingtip that offers advantages in high lift production and power efficiency. The investigation involved a multi-faceted approach, encompassing design, numerical analysis, manufacturing, and experimentation of two groups of wing models, including the dragonfly-like wings and baseline rectangular wings. CFD analysis revealed the significant impact of the sweep-back wingtip shape on the underlying aerodynamic mechanism, particularly the formation of a strong LE/TE vortex ring and vortex delay. Experimental testing of the wing models confirmed the validity of the design concept and provided data to validate the numerical models and results. Consequently, FSI analysis using the CFD-CSD simulations

was employed to analyse the effect of the reinforced wingtip structure. By comparing baseline rectangular wings with and without enhanced chordwise stiffness at the wingtip, the study analysed the elastic deformations of twist and bend and the resulting unsteady aerodynamic forces on the flexible FWR wings. The results of the numerical simulations and experiments showed that the reinforced wingtip is beneficial for maintaining lift production due to the enlarged pitching and flapping angles.

The study demonstrated the role of bending deformation in enhancing lift and power efficiency of FWR wings. The vortex delay mechanism was used to model wing bending deformation through delayed flapping motion. The method was validated by comparing variable stiffness along the wingspan with the experimentally measured stiffness of the present wings. The study found that flexibility with spanwise stiffness variation induced wing elastic deformation and moderately delayed flapping motion, resulting in desirable aerodynamic performance. The curving LE-beam forming the sweep-back and enclosed wingtip, which can be conveniently adjusted for thickness, provides a way to achieve variable stiffness and aerodynamic advantages for FWR-MAVs. By employing the designed dragonfly-like wings, the FWR model demonstrated high lift production and power efficiency across multiple flight tests. These findings contribute valuable insights for developing more efficient and agile flexible wings for FWR-MAVs.

Chapter 6 Multibody-Dynamic Modelling and Stability for a Bio-inspired FWR-MAV Performing Take-off-Forward Flight Mode Transition

Declaration: This chapter is entirely the author's independent work and does not include contributions from other team members.

Abstract

Flapping wing rotor micro aerial vehicles (FWR-MAVs) exhibit unique flapping and rotation motions, presenting challenges in flight control due to their complex dynamics and the constraints of size, weight, and power. This study focuses on investigating the stability characteristics of an FWR-MAV prototype that utilizes the high efficiency respectively in both FWR vertical take-off flight and bird-like forward flapping flight. In this research, a novel control mechanism is proposed for the FWR-MAV, which includes a bird-like tail and an actuator inducing mode transition from FWR to flapping-wing (FW) flight. Through flight simulations using multi-body dynamic software MSC.ADAMS/Simulink co-simulations interfacing with a quasi-steady aerodynamic method, the feasibility of mode transition from FWR to FW flight is validated. The study investigates the influence of flapping frequency, drive approach, and aerodynamic forces on flight stability. Detailed control methods, including model-based and model-free control, are discussed for further advancement in flight control systems. The results underscore the significance of active control systems in achieving attitude stabilization and highlight the potential of decoupling control techniques. These findings contribute to the improvement of flight stability and control capabilities in the development of FWR-MAVs.

Keywords: Flapping wing rotor, Multi-body dynamics, Stability analysis, Flight mode transition

6.1 Introduction

Drawing inspiration from the superior aerodynamic characteristics exhibited by natural aviators, Flapping-Wing Micro Aerial Vehicles (FW-MAVs) incorporate

these complex flight paradigms. With the expansion of our knowledge concerning unsteady aerodynamics at low Reynolds numbers and control strategies, numerous FW-MAVs have achieved practical flight capabilities. This progress has led to a significant enhancement in their agility, underlining the potency of this biomimetic strategy.

Flapping-Wing Rotors (FWR), a pioneering design within MAVs, amalgamate the strengths of bio-inspired flapping wings and rotary wings, boasting agile manoeuvrability along with Vertical Take-off and Landing (VTOL) and hovering capabilities. These innovative MAVs have shown substantial superiority over traditional FW designs by achieving high lift production and efficiency, as evidenced in recent studies (Guo et al., 2018; Wu et al., 2012, 2016; Zhou et al., 2018). Current FWR advances have enabled the transition from millimetre/milligram-scale prototypes to 60-g flight-capable vehicles. Their biomimetic form and diminutive size make them viable alternatives to commercial drones in civilian and industrial sectors, offering potential applications in intelligence, surveillance, and reconnaissance, aerial photography, and agricultural support (Lentink, 2013; Petricca et al., 2011; Zheng, Hedrick & Mittal, 2013).

While FWR-MAVs exhibit notable potential advantages, they also face substantial challenges. The rigorous size and weight restrictions associated with these vehicles pose complications in the integration of miniaturized systems, which can exacerbate control sensitivity and consequently hinder flight control performance. Additionally, the inherent complexities of FW flight augment the difficulties in conducting multi-body structural analysis, unsteady aerodynamic assessments, and the creation of periodic time-varying dynamic models - all crucial for the successful implementation of flight control systems (Keennon et al., 2012; Liang & Sun, 2013). Existing FWR models, due to unique wing kinematics, lack robust and reliable flight control systems, hindering stable controlled flight and particularly autonomous flight. Therefore, constructing a comprehensive flight dynamic model is essential to address these distinctive

challenges and enable agile manoeuvres, extensive flight envelopes, and compactness in FWR-MAVs.

Initial research into FW-MAVs employed standard aircraft equations of six degrees of freedom and a quasi-steady aerodynamic model to derive their equations of motion (Deng et al., 2006; Mahjoubi & Byl, 2013, 2014). These investigations underscored how unsteady aerodynamics, variable mass distributions, and highly nonlinear motions significantly influence the multi-body dynamic model. Studies such as those by Orlowski and Girard (2011) emphasized that the mass of the wings and inertial effects on the body, in conjunction with chosen aerodynamic modelling, greatly impact control analysis and simulation results. This led them to adopt D'Alembert's Principle for Multiple Rigid Bodies to generate motion equations for a FW system comprising three rigid bodies. Meanwhile, Lasek et al. (2002) simplified the multibody dynamics model of an insect-like FW vehicle using the Gibbs-Appel Equation, considering only two degrees of freedom: flapping and lagging. Grauer and Hubbard (2009) modelled a bird-like FW vehicle via Boltzman-Hamel Equations, considering a system of five rigid bodies including a fuselage body, two wings, and two tail pitch and roll linkages. In a separate approach, Shen et al. (2021) treated tail control surfaces as a part of the main body and simplified their bird-like FW vehicle into a three-rigid body model, allowing them to formulate dynamical equations using the recursive Newton-Euler method, bypassing complex symbolic differential procedures.

Beyond the above mathematical modelling approaches, Pfeiffer et al. (2010) accomplished flight simulations of a magpie-mimicked FW vehicle using multi-body dynamics software MSC.ADAMS and ANSYS to address the intricate fluid-structure interaction problem and evaluate the vehicle's longitudinal flight stability. Similarly, Lee et al. (2011) leveraged co-simulation of ADAMS and ANSYS to investigate the interplay between flapping frequency, forward flight speed, and other flight state behaviours of a bird-like FW vehicle. Their findings suggested that tail-wing's aeroelastic response could influence longitudinal flight stability, as an increase in flapping frequency amplified tail-wing vibration and decreased

body pitch vibration amplitude. Additionally, previous FWR studies (Chen et al., 2021; Guo et al., 2018) have demonstrated ADAMS' effectiveness in validating unique wing kinematics and flight dynamics characteristics, as evidenced by the congruence between flight trajectory simulation results and physical model test outcomes. These studies, however, focused on simulations of the FWR body without incorporating a tail or control surfaces.

Among the existing flight-capable FWR models, only a three-wing FWR model constructed by Dong et al. (2020) is equipped with an attitude control mechanism, which includes stabilizers and control surfaces situated below the FWR body. This setup mirrors the bird-like control mechanism of the DeFly Explorer (Ma et al., 2013). They primarily demonstrated the vehicle's hovering and forward flight capabilities by adjusting the gains of the PID controller in a series of flight experiments. Nevertheless, the intense oscillation from wing motions posed challenges for maintaining the desired attitude during manoeuvres. Subsequently, they developed a motor direct-drive twin-wing FWR model that accomplished attitude adjustment and vehicle stabilization through differential wing movements, focusing on the development of an active feedback system integrating microelectromechanical Systems and a vision-based motion capture system (Dong et al., 2022). Although the independent flapping motions of the two wings resemble a bird's beat, this FWR platform utilizes a tailless control strategy, a feature inspired by insect flight dynamics. However, the absence of tail stabilizers makes the flight of this tailless insect-like vehicle inherently unstable and complex. Given the existing challenges faced by FWR models in achieving stable flight, this study introduces a control mechanism designed for the present FWR model. The feasibility of this control mechanism is validated through flight simulations utilising ADMAS.

Even though bird and insect flights differ in attitude and flight controls, a bio-inspired FWR-MAV can leverage advantages from both flight behaviours. It can execute aerodynamically and power-efficient take-off and hovering using the FWR mode, while performing agile forward flight using the FW mode with straightforward control akin to a bird. Compared to rotary wings, the bird-like

flapping forward flight has better aerodynamic efficiency and faster flying speed. On the basis of these, the proposed control mechanism presented in this study enables the FWR-MAV to perform vertical take-off and bird-like flapping forward flight through a mode transition actuator that reserves one of the asymmetric FWR wings for the symmetric flapping wing layout. This study focuses on investigating the dynamic behaviour and stability during take-off and mode transition based on an FWR model.

This chapter is organized as follows: Section 6.2 provides a description of the vehicle prototype, including its two modes and the proposed attitude control mechanism, along with the modelling procedure. In Section 6.3, the flight simulation and stability analysis of the vehicle prototype are presented. This includes an examination of uncontrolled flight conditions and controlled flight conditions, particularly the feasibility of the proposed control mechanism through the implementation of tail motion. The challenges encountered in flight dynamics and control are discussed in Section 6.4, which outlines the detailed control approach for further development of the control system. Section 6.5 summarizes the key contributions and insights for the novel design of the FWR-MAV.

6.2 FWR-MAV Multi-body Dynamic Model

6.2.1 Description of the FWR-MAV Prototype

Figure 6-1 depicts the FWR-MAV prototype introduced in this paper, based on the FWR model with bifurcated units developed in Chapter 4 (FWR Model.3, as denoted in Figure 1-2). To investigate the flight dynamics characteristics of the prototype, precise measurements of the dimensions and mass were conducted for each component of the physical model, encompassing the wing, DC motor,

servomotor, frame, etc., as listed in

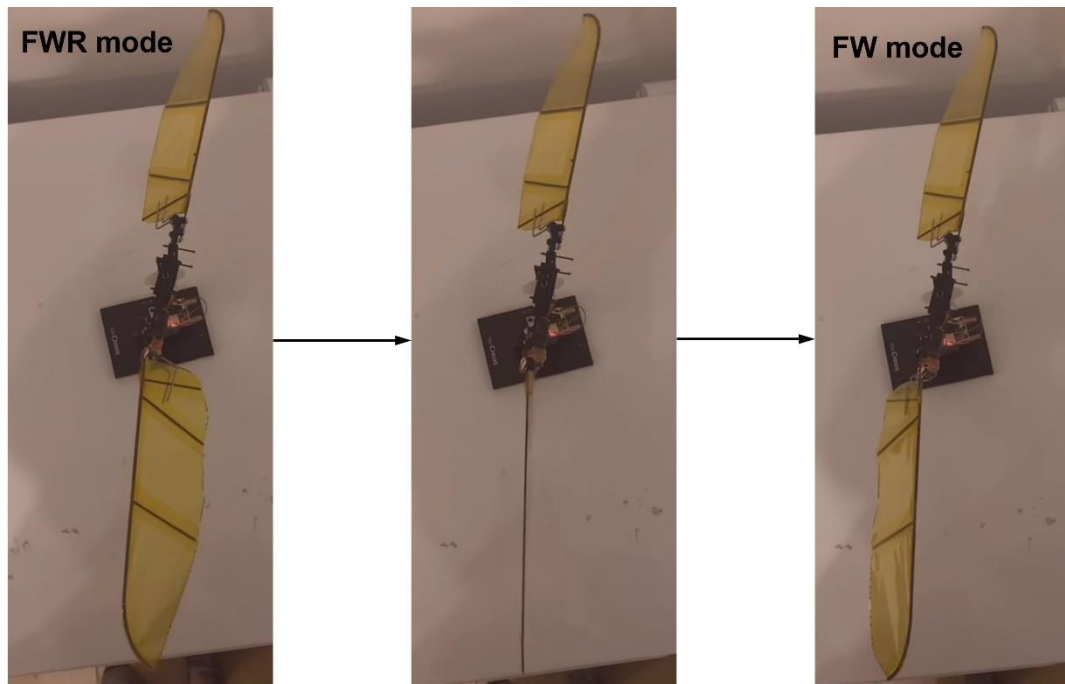
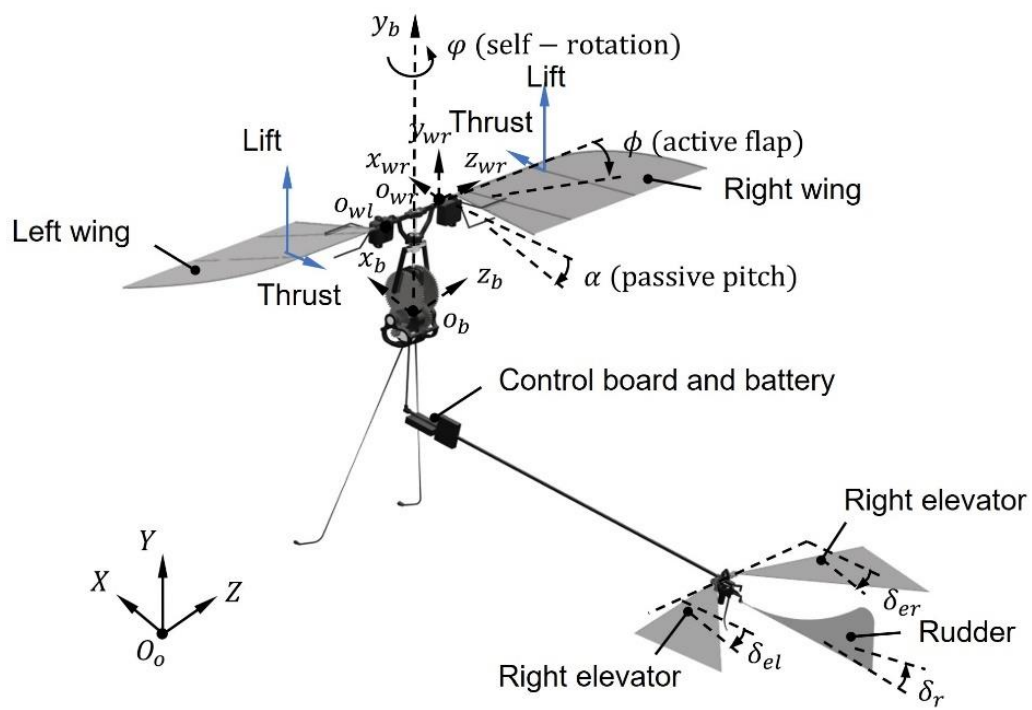


Figure 6-2 Ground test of flight mode transition from FWR mode to FW mode.

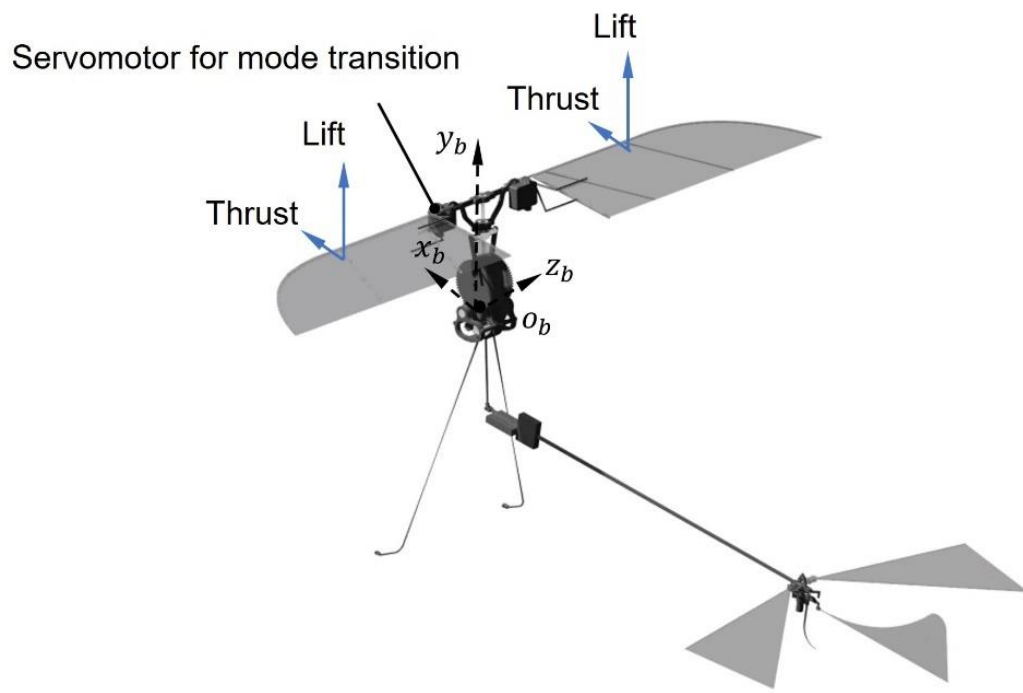
Table 6-1. The body length of the prototype, measured from the front leg to the end of the tail rudder, is 393 mm. The height of the prototype is 212 mm. Based on measurements and recorded data from structural components and onboard devices, the prototype total weight is estimated to be approximately 41 g. The primary body of the prototype comprises the driving, translation and flapping mechanisms responsible for the two wing motions. Two sets of two-stage reduction gears, driven by individual DC motors, are employed to collectively actuate the high-frequency wing flapping motion and enhance the loading capacity of the system. The tail motions of elevator and rudder are actuated by three servomotors.

For flight mode transition, a servomotor is connected to the bifurcated unit located at the wing flapping bar, enabling the left wing to undergo a 180° rotation. This transition transformed the wing from the initial FWR layout to the FW layout, as depicted in Figure 6-2. In flight simulation, the prototype execute take-off flight using the FWR mode (Figure 6-1(a)) and forward flight using the FW mode (Figure 6-1(b)). In FWR mode, active flapping motion of the asymmetrical wings

generates both lift and thrust. This asymmetrical thrust induces a rotational moment around the central line of the primary body, enhancing the aerodynamic efficiency during take-off or hovering. On the other hand, in FW mode, the symmetrical wings execute vertical flapping motion, generating lift and forward thrust, simulating bird-like forward flight. Through ground tests, Figure 6-2 has demonstrated the feasibility and practicality of the physical FWR model with bifurcated units and an additional servomotor to accomplish the mode transition between FWR and FW layouts.



(a) FWR mode



(b) FW mode

Figure 6-1 MAV prototype with FWR mode and FW mode.

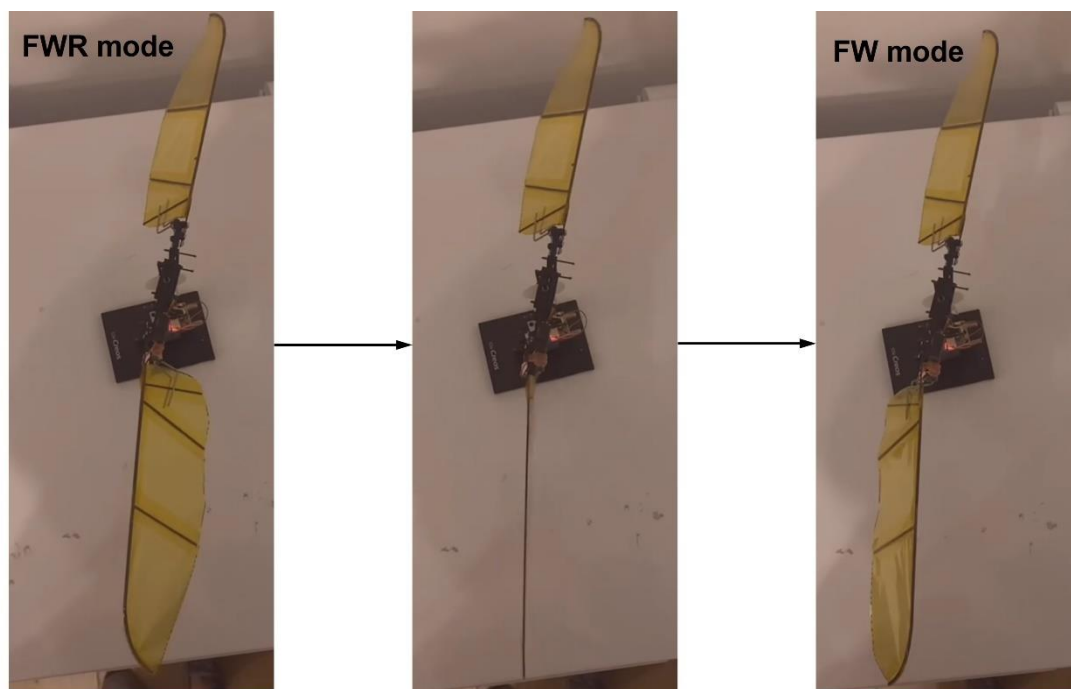


Figure 6-2 Ground test of flight mode transition from FWR mode to FW mode.

Table 6-1 List of the MAV prototype components.

Component	Material	Number	Unit Dimension (mm)	Unit Weight (g)
Wing	Polyimide & cardon fibre	2	165 × 60	1.33
Elevator fan	Polyimide & cardon fibre	1	105 × 60	0.19
Rudder fan	Polyimide & cardon fibre	2	102 × 36	0.13
Primary body frame & gears & cranks & bearings & linkages & shaft & legs	Polyamide, plastic, cardon fibre, aluminium	1	54 × 28 × 212	13.25
3.7 V AFRC-D1302 Servomotor for wing	-	2	13.5 × 6.2 × 20.1	1.7
3.7 V DC motor	-	2	20.3 × 8.5	4.87
3.7 V 150mAh lithium battery		1	28 × 20 × 7	6.05
Turtlebee F3 Control board	-	1	29.2 × 29.2	4
Tail joints	Plastic	1	20 × 8 × 46	0.23
MetaFly Servomotor for tail	-	3	10 × 4	0.35
Total weight				40.83 g

6.2.2 Definition and Assumptions for Rigid Multi-body Dynamics

As shown in Figure 6-1, the multi-body model of the FWR-MAV prototype comprises five primary parts: the primary body, two wings, two elevator fans, and a rudder fan. The orientation and position of the prototype are defined with

respect to the inertial absolute coordinates O_oXYZ , which are fixed to the ground. The body-fixed coordinates $o_bx_by_bz_b$ are positioned at the centre of mass of the prototype. The attitude of the prototype body is determined by the pitch angle θ , roll angle β , and yaw angle γ , as shown in Figure 6-3.

The wing kinematics, encompassing flapping angle ϕ , pitching angle α , and rotation angle ψ , are defined by the coordinate $o_wx_wy_wz_w$ situated at the wing root. The motions of elevator and rudder are governed by angles δ_e and δ_r , respectively, with their orientations aligned with the body-fixed coordinate system.

Therefore, the dynamic model can be determined using the generalized coordinates $q = [p_x, p_y, p_z, q_x, q_y, q_z, \psi, \phi, \alpha_l, \alpha_r, \delta_{el}, \delta_{er}, \delta_r]^T \in R^{13}$, where (p_x, p_y, p_z) denotes the position of the centre of mass of the body o_b , and the orientation is determined by the Euler angles (q_x, q_y, q_z) following the body rotating order 'ZYX', i.e., (θ, β, γ) . The equations of motion for the prototype can be expressed in the general form based on a hybrid of Euler and Lagrange methods for the multi-body system (Deng et al., 2006; Lee et al., 2011; Mahjoubi & Byl, 2014; Shen et al., 2021) as follows:

$$M(q)\ddot{q} + C(q, \dot{q})\dot{q} + G(q) = Q \quad (6-1)$$

Here, $M(q) \in R^{13 \times 13}$ denotes the inertia matrix, $C(q, \dot{q}) \in R^{13 \times 13}$ represents the Coriolis matrix, $G(q) \in R^{13}$ denotes the gravity vector, and $Q \in R^{13}$ represents all generalized applied forces.

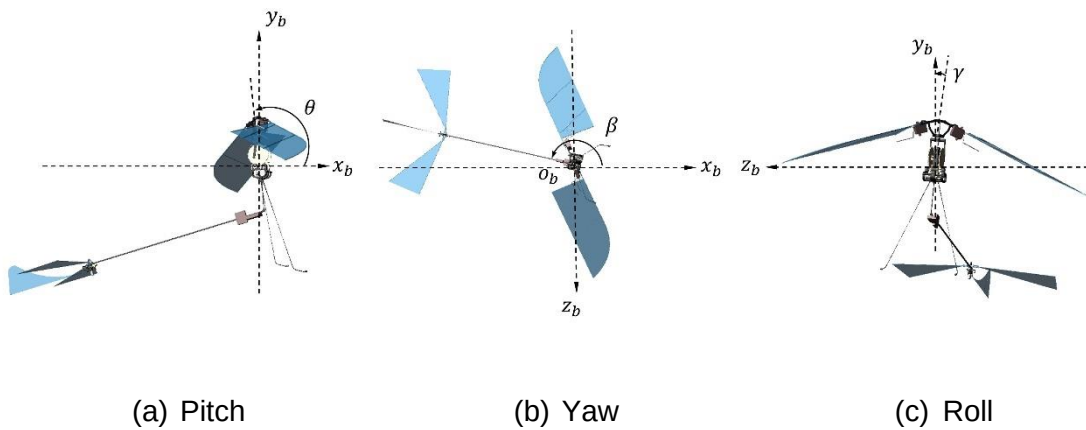


Figure 6-3 Definition of prototype body attitudes

To model the flight of the prototype, certain assumptions are made as preconditions:

1. The wing is treated as a rigid body without elastic deformation. The aerodynamic forces acting on the wing are computed instantly using a quasi-steady aerodynamic model for both FWR and FW modes, utilizing wing kinematics based on experimental data. The flapping motion keeps a constant flapping frequency for each mode.
2. In line with practical servomotor operation, the left wing undergoes a transition in mode with a rotational velocity of 10° per 0.01 s. During this transition, the wing rotation joint is constrained, and the aerodynamic forces are calculated using the FW mode for each wing, considering defined flapping, and pitching motions. The aerodynamic effects resulting from the reserve rotation velocity of the left wing are disregarded.
3. The rotational speed of the servomotors controlling the tail fans is disregarded, and the aerodynamic forces resulting from the velocity of tail joints on the tail fans are neglected.

6.2.3 Wing Kinematics Definition and Aerodynamic Model

The flapping motion of the physical mechanism is governed by the following equation:

$$\phi(t) = r[(1 - \cos(\omega t)) + 0.25\lambda(1 - \cos(2\omega t))]/a - \phi_0 \quad (6-2)$$

where ϕ_0 represents the initial flapping angle at the maximum stroke, $\lambda = r/l$ is the ratio of the crank arm length r to the connecting rod length l , a is the length of the flapping bar, ω is the flapping velocity, and t represents the instant time, as mentioned in Chapter 4. In the current mechanism, the flapping motion has an amplitude of 65° , with a flapping angle ϕ ranging from $+30^\circ$ to -35° . Experimental findings from the physical FWR model suggest that the rotating frequency closely matches the flapping frequency. For the purpose of simulation, it is assumed that the rotating velocity $\dot{\psi}$ remains constant over a flapping cycle.

The passive pitching angle variation in the FWR model has been experimentally validated (Chen *et al.*, 2021). During the upstroke, the wing's pitching angle α rapidly increases to its maximum value α_{max} under the influence of aerodynamic pressure and inertial forces. This maximum angle is maintained throughout the remainder of the upstroke. Subsequently, during a short period between the end of the upstroke and the start of the downstroke, the wing undergoes an opposite rotation, resulting in the minimal pitch angle α_{min} . In this study, due to the imposed bifurcated unit of angle limitation, the passive pitch angle α varies between $\alpha_{min} = 7^\circ$ and $\alpha_{max} = 40^\circ$.

The aerodynamic forces acting on the wings are determined using a quasi-steady aerodynamic model, which is then interfaced with ADAMS as force inputs. The details of the aerodynamic model can be found in the previous study (refer to Chapter 4). To calculate the total force on a wing, the wing is divided into infinitesimal blades of thickness dr . On a 2D wing blade, the aerodynamic forces in the local wing-fixed coordinate system $o_w x'_w y'_w z'_w$, which is transformed from the wing's inertial coordinate system $o_w x_w y_w z_w$ using the matrix $\mathbf{R}_{i \rightarrow w} = \mathbf{R}_\alpha^T \mathbf{R}_\phi^T \mathbf{R}_\psi^T$, are computed using the following equations:

$$dF_{x'_w}(t, r) = \{0.5\rho_{air}|\mathbf{U}|^2 C_H c(r) + (\lambda_z u_z \omega_x - \lambda_{z\omega} \omega_x^2)\}dr \quad (6-3)$$

$$dF_{y'_w}(t, r) = \{0.5\rho_{air}|\mathbf{U}|^2 C_V c(r) + C_{rot}|\mathbf{U}|\omega_x c(r)^2 + (-\lambda_z \dot{u}_z - \lambda_{z\omega} \dot{\omega}_x)\}dr \quad (6-4)$$

where ρ_{air} is the air density; $|\mathbf{U}|$ denotes the *Euclidean* norm of the translational velocity, with $\mathbf{U} = r[\omega_z \quad -\omega_y]^T$, which can determine the effective angle of attack $\alpha_e = \arctan(-\omega_y/\omega_z)$; C_H , C_V and C_{rot} are the quasi-steady aerodynamic coefficients due to wing translation and wing pitching (empirical coefficients); λ_z and $\lambda_{z\omega}$ denote the added mass coefficients, given by $\lambda_z = \pi/4\rho_{air}c(r)^2$ and $\lambda_{z\omega} = \pi/4\rho_{air}hc(r)^3$, respectively.

The lift and drag forces on the i^{th} tail fan can be calculated as follows:

$$F_{L_i}(t) = 0.5\rho_{air}|\mathbf{U}_i|^2 C_{L_i} S_i \quad (6-5)$$

$$F_{D_i}(t) = 0.5\rho_{air}|\mathbf{U}_i|^2 C_{D_i} S_i \quad (6-6)$$

where C_{L_i} and C_{D_i} are the lift coefficient and drag coefficient of the i^{th} tail fan respectively, based on the thin flat plate theory; $\mathbf{U}_i$ is the translational velocity of the i^{th} tail fan, and S_i is the area of the i^{th} tail fan.

6.2.4 Flight Dynamic Simulation Architecture

The flight dynamics simulation of the FWR-MAV prototype is realized through a combined ADAMS/Simulink simulation. The simulation architecture comprises five main components: two actuator parts, an aerodynamic module, a MAV multi-body dynamic module, and a controller part, as depicted in Figure 6-4.

The flapping actuator generates motor motions for driving the wing mechanism, while the tail actuator converts the control signal into rotational motion for the tail fans. The aerodynamic module utilizes the motion signals from the actuator parts to compute the instantaneous aerodynamic forces acting on the wings and tail fans, which are used as input variables for the ADAMS motion functions. The ADAMS model simulates the flight of the vehicle based on the motions and aerodynamic forces, providing outputs of the vehicle's six degrees of freedom that are sampled by the controller part. The controller part, based on the motion signals of the vehicle body, generates control signals for the tail actuators to appropriately respond.

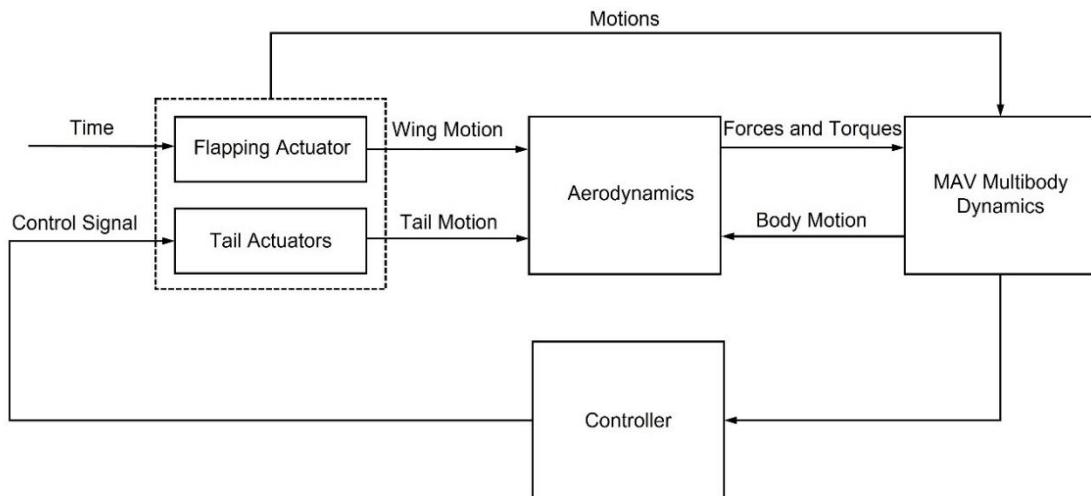


Figure 6-4 Block diagram of the simulation architecture for the FWR-MAV prototype

6.3 Flight Simulation and Stability Analysis

6.3.1 Take-off Flight of the Tailless FWR Model

The vehicle prototype's total weight necessitates a flapping frequency exceeding 10 Hz to generate sufficient lift for take-off. Consequently, uncontrolled flight simulations of the FWR model are performed on the tailless vehicle prototype at frequencies of 12 Hz and 16 Hz to evaluate its inherent stability. The absence of a tail allows the FWR model's centre of mass to align with the longitudinal central axis, enabling vertical take-off.

The flight characteristics of the FWR are closely tied to its mechanical system, with the motions, interactions between components, and mass distribution significantly influencing the vehicle's attitude and balance. Comparing Figure 6-5 and Figure 6-6, it is observed that when the FWR adopts a driving mode with dual motors rotating in the same direction, instability occurs earlier compared to the mode with dual motors rotating in opposite directions. Due to the high load on the FWR model, a substantial drive torque is required from the motors. Reversing the rotation of the twin motors ensures that the rotational torques cancel each other out, mitigating the influence of rotational inertia on the body and allowing it to maintain its attitude. Furthermore, the body's yaw is affected by the wing rotation motion, with the orientation depending on the approach used for dual motor driving. This occurs because the forces/torques from the motors act on the two cranks of the translation mechanism, leading to changes in body attitude. Consequently, despite the absence of friction in the mechanical system, the inherent mechanical relationships can render the FWR prone to instability.

The flight dynamics of the FWR is strongly influenced by the time-varying velocity during take-off and the instantaneous production of aerodynamic forces. In Figure 6-5 and Figure 6-6, it is also evident that the FWR model with a higher flapping frequency tends to experience earlier instability and loss of balance, as the aerodynamic forces and torques on the body increase. Thus, as shown in Figure 6-5, the FWR model driven by reserved rotation motors demonstrates its capability to achieving vertical take-off with a flapping frequency of 12 Hz and

maintains longitudinal stability for a period with an increased flapping frequency of 16 Hz.

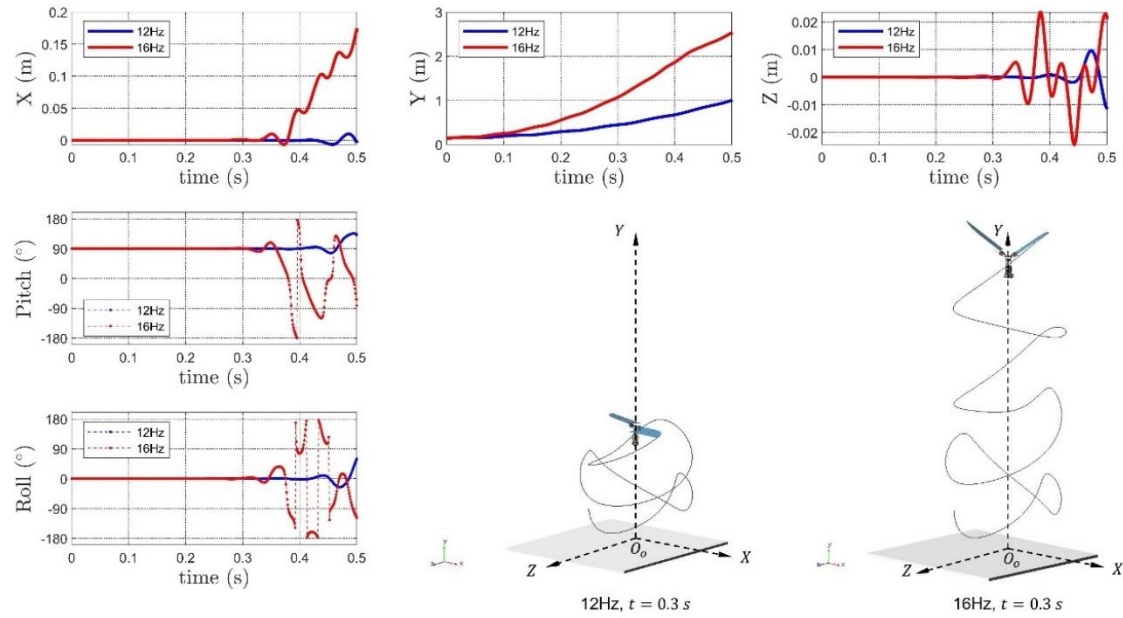


Figure 6-5 Uncontrolled take-off flight of the tailless FWR model driven with reversed-direction drive motors

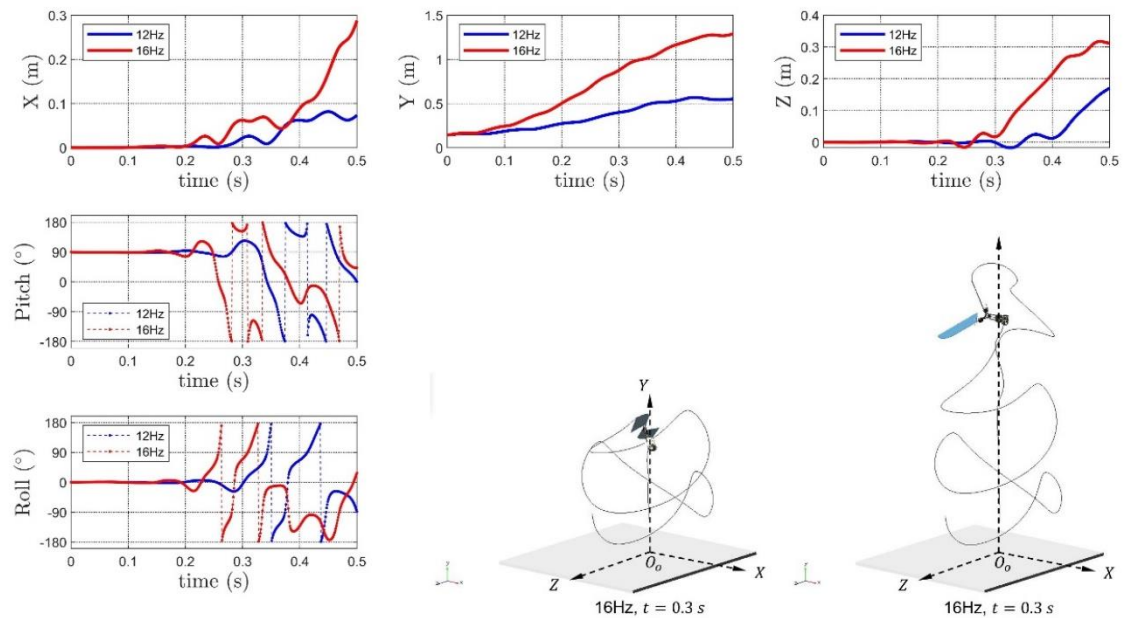


Figure 6-6 Uncontrolled take-off flight of the tailless FWR model driven with same-direction drive motors

6.3.2 Stability Analysis of Flight Mode Transition

The incorporation of control surfaces at the tail is essential for achieving the desired bird-like control strategy in the FWR-MAV. However, the FWR mechanical system, coupled with wing kinematics and unsteady aerodynamic forces, presents challenges in maintaining stable attitude. Furthermore, the arrangement of the tail results in the centre of mass of the vehicle being offset from the central axis of the FWR body. As a result, the lift and thrust generated in both FWR mode and FW mode induce torques around the vehicle's centre of mass. This introduces complexity in the flight simulation of the vehicle prototype with a tail, leading to significant periodic attitude changes, as shown in Figure 6-8.

To enable the transition from FWR mode to FW mode, elevator controls are utilized to regulate the vehicle's rotational movements, as shown in Figure 6-7. Roll control is achieved by manipulating the angles of the left and right wings, generating counter torque to counteract body rotation. To stabilize the attitude angles and prevent excessive rotations, a cascade PID control structure is employed, consisting of an open-loop position controller and an angular velocity controller.

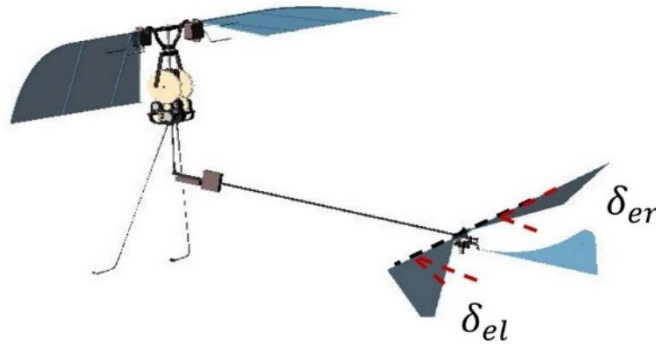


Figure 6-7 Diagram of the elevator fan motion for stability

In Figure 6-8, the vehicle exhibits take-off flight in FWR mode with a flapping frequency of 16 Hz from 0 to 0.5 s. During this period, the vehicle demonstrates longitudinal stability but with oscillations in pitch and roll. In comparison to the tailless model, the yaw of the vehicle is relatively constrained due to mechanical inertial effects. From $t = 0.5$ s to $t = 0.62$ s, the left wing undergoes reversal and

both wings maintaining a horizontal position without flapping, resembling a gliding motion until $t = 1$ s. Notably, a smooth mode transition with relatively stable pitch and roll is observed when the elevator is rotated 30° (Figure 6-9(b)). Conversely, in Figure 6-9(a) without elevator controls, excessive pitch and roll rotations lead to continuous scrolling of the vehicle. Furthermore, the controlled flight demonstrates a tendency for the yaw to converge, suggesting the possibility of forward flight in the indicated direction.

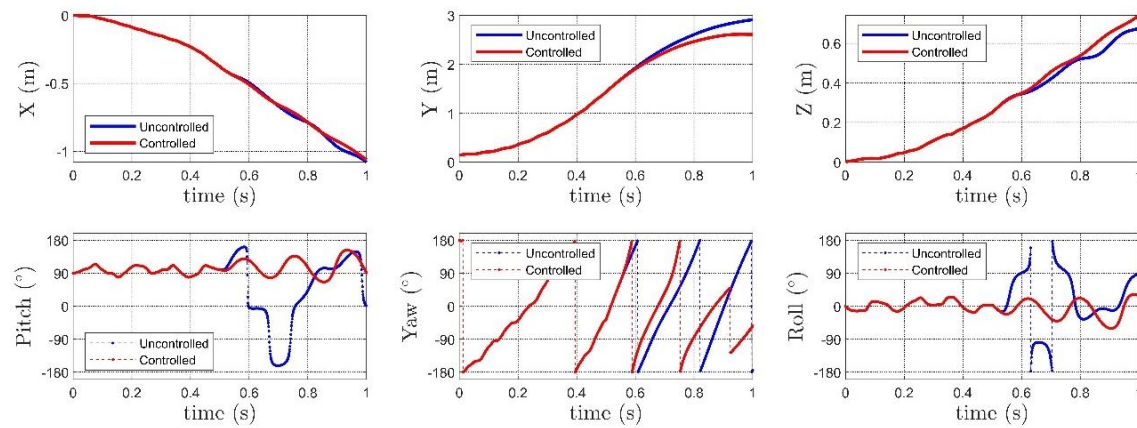


Figure 6-8 Simulation of take-off flight in FWR mode

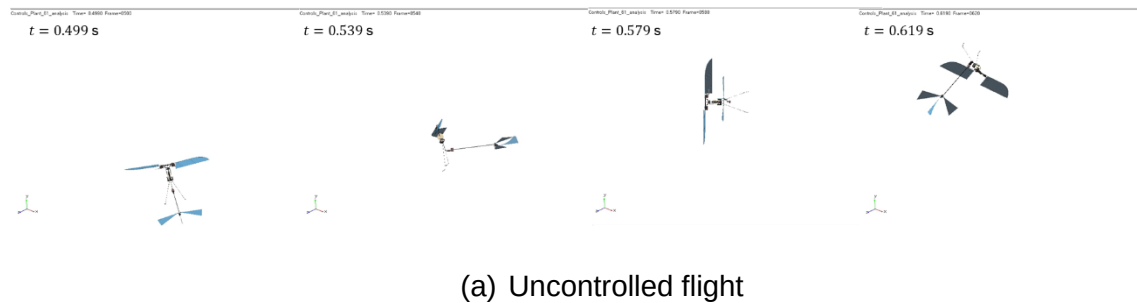
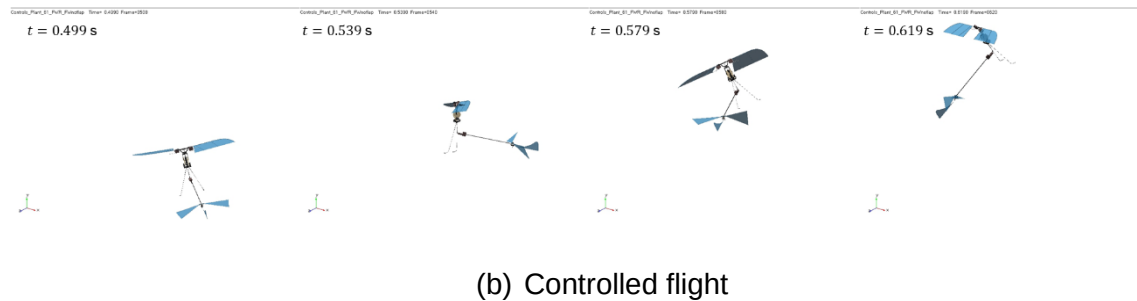


Figure 6-9 Simulations of flight mode transition without and with a tail control

6.3.3 Flight Simulation of Take-off to Forward Flight

Based on the aforementioned controlled flight method, the simulation duration is extended to encompass the complete flapping forward flight of the vehicle after the mode transition. In this case, the vehicle takes off in FWR mode from 0 to 1 s, followed by a mode transition at 1.12 s. It then proceeds to continuously fly forward using active flapping motion. Given the initially low horizontal velocity during the forward flight, the flapping wings exhibit suboptimal aerodynamic efficiency. Therefore, the flapping frequency is increased to 40 Hz to generate sufficient lift to balance the weight, while the forward thrust produced by the defined flapping motion is approximately equal to the lift.

Figure 6-10 demonstrates the vehicle's attitude throughout the entire flight, starting from take-off and transitioning to forward flight. The take-off phase of the vehicle is dynamically stable, but after the mode transition, the body experiences severe spinning motion during forward flight. This continuous spinning behaviour is caused by the rotational moment generated by the wing thrust acting on the vehicle's centre of mass. Moreover, the vehicle remains in an unstable state even in the absence of aerodynamic forces, resulting in the body's rotation due to inertial effects induced by mechanism. Unlike conventional bird-like FW vehicles that can stabilize their attitude and achieve forward flight with an initial forward velocity (e.g., by being thrown forward by hands), the FWR model transitioning to FW mode lacks a stable initial condition and forward velocity, making it more susceptible to rotational mass moment of inertia.

Figure 6-10 also depicts the flight trajectory of the vehicle prototype, indicating a spiral forward motion within the vertical X-Y plane in FW mode. Despite this undesired behaviour, the vehicle exhibits longitudinal stability during its forward flight along the X and Y axes.

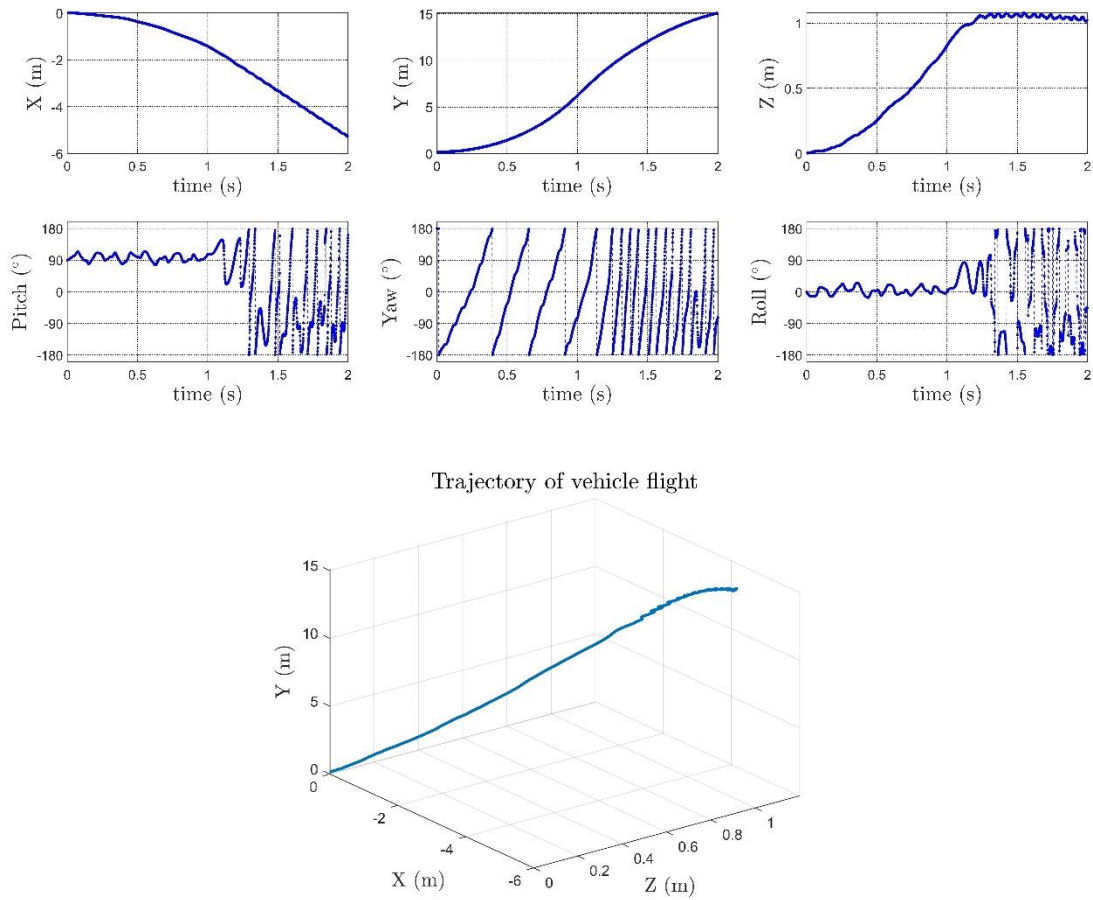


Figure 6-10 Simulation of the entire flight from take-off to forward flight

6.4 Further Development of Control Approach

The development of a control system for FWR-MAVs presents challenges in two main aspects: wing motion and inherent instability, along with constraints related to scale, weight, and power. This study focuses on exploring the stability problem of the FWR, considering its highly nonlinear and time-varying dynamics in complex environments. It is observed that accurately controlling the multi-body dynamics of the FWR-MAV and achieving the trimmed level flight after mode transition solely through ADAMS simulations can be challenging. To address these issues and enhance robustness, decoupling control strategies can be employed to provide specific solutions to the flight dynamics and control problem of FWR-MAVs.

Two alternative control methods with aspect to model-based control and model-free control can be explored for further development of flight control systems for FWR-MAVs. Building upon the ADAMS model used in this study, the following steps can be taken to extend the present prototype model:

- 1) Develop a multi-body model for flight dynamics and derive the equations of motion of the vehicle with a quasi-steady aerodynamic model.
- 2) Apply the Floquet Theory to analyse the stability of the vehicle by treating the flight as a cyclic-motion equilibrium. The Floquet Theory uses a system of linear ordinary differential equations with time-periodic coefficients to assess the stability of small perturbations in the state variables. Stable periodic solutions show decaying perturbations over time, while unstable solutions exhibit growing or persistent perturbations. Previous studies have successfully applied this theory to analyse stability in insect hovering flight (Wu & Sun, 2012) and adjust wing kinematics for stabilized flight (Bhatia et al., 2014; Stanford et al., 2013).
- 3) Employ simplifying assumptions to decouple the body motion based on pitch, roll, and yaw, allowing for analysis of each dynamic characteristic. Model-based control algorithms such as LQG method (Deng et al., 2006), PID control (Loh et al., 2003), frequency modulation (Doman et al., 2010), state feedback techniques (Tahmasian et al., 2014), nonlinear control (Khanmirza et al., 2012), and adaptive control (Li & Duan, 2012) can be employed.
- 4) Conduct flight tests to validate the proposed methods for precise attitude and position, refining the controller or expanding to other dimensions of motion.

Another control approach is based on model-free adaptive variable structure control (Hou & Wang, 2013; Zhang et al., 2017). This model-free control system relies solely on input/output measurement data of the plant, without explicit reliance on a model. It may utilize implicit information about system dynamics or structure. This approach eliminates the need for modelling processes,

consideration of time-varying parameters, and unmodeled dynamics. To implement this approach, a mathematical model of the multi-body dynamics and equations of motion must also be established. The FWR-MAV dynamics can be transformed into a sequence of equivalent local dynamic linearization models known as pseudo-partial derivatives (PPD) (Hou & Jin, 2011). After the PPD matrix is estimated, an optimal criteria-based model-free control law is designed for trajectory control. If the convergence rate of the tracking error is slow during this process, a reset algorithm is needed to enhance the effectiveness of the parameter estimation algorithm in tracking time-varying parameters. (Khosravi & Novinzadeh, 2021).

In summary, attitude stabilization is a crucial aspect in the autonomous flight of FW MAVs (Wagter et al., 2014). An FWR-MAV also necessitates an active control system to adjust wing kinematics during flapping motion and generate control torque to achieve desired attitude changes. This study focused on analysing the stability issues the present FWR model and proposing a control mechanism, serving as a step towards designing of dedicated control system for the applicable FWR-MAV. The aforementioned control methods provide insights for further improvement work.

6.5 Conclusion

The FWR model is theoretically statically stable in the X-Y plane of the inertial absolute coordinates, as it does not require actuation torque for wing rotation. However, during flight simulations and previous free flight tests, the FWR model exhibited swinging and spinning behaviour. To investigate the flight stability characteristics of the FWR-MAV prototype and validate the feasibility of the mode transition from FWR to flapping wings, flight simulations using ADAMS/Simulink were conducted. These simulations integrated the unique wing kinematics and quasi-steady aerodynamic model of the FWR. The results demonstrate the effectiveness of the co-simulation approach in rapidly estimating the flight performance of the FWR and providing guidance for the design of flight control mechanisms in the development of the FWR-MAV. The study findings demonstrate the following key insights and conclusions:

- The present FWR mechanical model demonstrates longitudinal stability during flight. The flight dynamic stability is influenced by the drive approach and flapping frequency. The motor-driven mechanism can introduce instability, which can be mitigated by using reversed-rotation dual motors. However, as the flapping frequency increases, the flight of the FWR model becomes oscillatory, making it challenging to maintain body attitude under high aerodynamic and inertial loads. This can lead to a loss of balance and spiral motion.
- The FWR-MAV prototype, equipped with a tail and employing a bird-like control strategy, experiences rotational moments induced by the aerodynamic forces of the wings relative to the body's centre of mass. This results in dynamic variations in pitch and roll angles, while the yaw velocity is slower compared to the tailless model. Inertial forces from the mechanism system significantly affect the vehicle's motion and attitude.
- During the mode transition, the pitch and roll attitude of the prototype can be effectively stabilized by employing the differential rotation angle of the two elevators. This counteracts the body's rolling motion and prevents overturning and spinning.
- While the FWR-MAV prototype does not achieve the same level of stabilized attitude angles as bird-like flapping flight in the simulations, the overall flight from take-off to transition to FW forward flight has been successfully simulated with dynamic stability. This demonstrates the feasibility of the proposed control mechanism.
- The flight of the FWR-MAV involves intricate multi-body dynamics and significant coupling between aerodynamics and attitude angles. This study highlights the challenges and provides recommendations for further flight control design work aimed at enhancing flight stability and control capabilities of the FWR-MAV prototype.

Chapter 7 Conclusions and Future Work

The overall findings of this research highlight the enhanced aerodynamic efficiency and performance of bio-inspired flapping wing rotors, achieved through aerodynamic and structural analyses and experiments. This has significantly advanced the development of flapping wing rotor micro aerial vehicles (FWR-MAVs) during the study period, progressing from initial ground tests to tethered flights, further advancing to achieve untethered vertical take-off and free flights with onboard devices, and significantly increasing the model's take-off weight. The following specific conclusions are drawn in alignment with the original objectives outlined in the Introduction.

7.1 Remarks on Objective 1

- Two mechanical FWR models incorporating flapping, pitching, and rotation motions were designed, manufactured, tested, and analysed to increase aerodynamic efficiency, as presented in Chapter 3. The high-speed camera and load-cell measurement system validated the FWR mechanism for fulfilling pre-defined and optimal wing kinematics of motion, enabling sufficient lift production to overcome self-weight for flight.
- Passive pitching angle variation, driven by inherent aerodynamic and inertial forces, was found to significantly increase lift production and aerodynamic efficiency through analysis and experimental study. A novel sleeve-pin unit mounted on the flapping mechanism was validated as an effective method to achieve pre-defined flapping and pitching motions for desirable aerodynamic performance.
- For an FWR with PPAV, the experimental study demonstrated that self-propelled rotation contributed to 30% of lift production, significantly different from conventional flapping wings.
- Asymmetric flapping stroke amplitudes were identified as another key factor for enhancing lift in the present mechanical FWRs, demonstrated through experimental analysis and flight tests. Various free flights of the present FWR-MAVs, representing significant progress as summarized in

Chapter 2, demonstrated the effectiveness of PPAV and asymmetric stroke amplitudes for improving FWR aerodynamic performance.

7.2 Remarks on Objective 2

- To enhance the aerodynamic and power efficiency of existing FWR-MAVs, an elastic mechanism was proposed and analysed using a nonlinear dynamic model coupled with unsteady aerodynamic analysis of FWR, as presented in Chapter 4. The analytical model was validated through experimentation, emphasizing the resonant frequency of the FWR model, determined by the mechanical system's mass distribution and spring stiffness. Power consumption was strongly correlated with the inertial force induced by wing acceleration and deceleration. Incorporating springs into the FWR mechanism proves advantageous for actuating wing motions, resulting in reduced power consumption.
- The analytical model revealed that input power could be reduced by 50% at resonance compared to the baseline system without a spring. Additionally, integrating an optimally stiff spring could result in a 20%-35% reduction in power consumption and an increase in power efficiency by up to 77% at high flapping frequencies.
- Experiments demonstrated that additional power was required for aerodynamic lift force generation compared to the purely mechanical system where the skin membrane had been removed from the wings. Ultimately, the elastic FWR mechanism achieved a 14% input power reduction and 16% power efficiency with wing skin and a 0.036 N/mm stiffness spring compared to the baseline springless model at the same flapping frequency of 8.1 Hz.
- Compared to a previous FWR model with similar weight and size, which only achieved untethered flight at a high input power, the current FWR model demonstrated a 20% reduction in power consumption and a 66.7% increase in power efficiency, successfully achieving controlled free flight using an onboard power unit and remote-control device.

7.3 Remarks on Objective 3

- A bio-inspired flexible wing was proposed for FWR-MAVs with the goal of enhancing aerodynamic performance as presented in Chapter 5. The FWR wing featured a dragonfly-like shape with a sweep-back wingtip. A comprehensive approach, including design, numerical analysis, manufacturing, and experimentation of two wing model groups (dragonfly-like wings and baseline rectangular wings), unveiled the significant impact of the sweep-back wingtip on aerodynamics.
- Numerical simulations and experimental measurements examined the elastic deformation of the dragonfly-like wing structure and its unsteady aerodynamics for FWR. Fluid-structure interaction (FSI) analysis assessed the effects of the reinforced wingtip, showing that it is beneficial for maintaining lift production due to the enlarged pitching and flapping angles.
- The research demonstrated the role of bending deformation in enhancing lift and power efficiency of FWR wings. Flexibility with spanwise stiffness variation induced wing elastic deformation and moderately delayed flapping motion, resulting in desirable aerodynamic performance. The curving LE-beam forming the sweep-back wingtip provides a way to achieve variable stiffness and aerodynamic advantages for FWR-MAVs.
- By employing the designed dragonfly-like wings, the FWR model demonstrated high lift production and power efficiency across multiple flight tests. These findings contribute valuable insights for developing more efficient and agile flexible wings for FWR-MAVs.

7.4 Remarks on Objective 4

- Based on a free-flight-capable FWR mechanical model that was investigated in Chapter 4, the FWR-MAV prototype equipped with a tail control mechanism and mode transition actuator for controlled VTOL and forward flight was presented in Chapter 6. The study investigated the flight dynamics and stability characteristics of the vehicle prototype, validated

the feasibility of the novel mode transition from FWR to flapping wing flight, and explored control approaches for further development.

- The utilization of co-simulation in ADAMS/Simulink with a quasi-steady aerodynamic model was emphasized to rapidly assess flight performance and evaluate control mechanisms for the successful design and operation of the FWR-MAV.
- The developing FWR mechanical model demonstrated its longitudinal stability during flight, considering factors such as drive approach, wing kinematics, aerodynamic forces, and inertia. These findings contribute to a better understanding of FWR flight dynamics.
- The successful simulation of the mode transition with relatively stabilized pitch and roll attitude was achieved through the implementation of the tail control mechanism. Although the FWR-MAV prototype was unable to achieve the same level of stabilized attitude angles as bird-like flapping flight in the simulations, the overall flight from take-off to transition to FW forward flight demonstrates dynamic stability and validates the feasibility of the proposed control mechanism.
- The research explored the control and stability challenges of the FWR-MAV, aiming to identify potential control approaches for improving the vehicle's flight performance and stability.

7.5 Suggestions for Future Work

This thesis has explored various investigations and methodologies aimed at enhancing the aerodynamic performance and efficiency of FWR-MAVs for flight applications. Specifically, it has addressed lift augmentation, power efficiency, and bio-inspired aeroelasticity in the design and development of FWR-MAVs.

Although the current FWR models, featuring the sleeve-pin unit and U-shaped mechanism for PPAV and flapping motions, have been identified as effective in this thesis and have achieved a series of successful flights with significantly increased take-off weight, they are equipped only with a radio receiver for free flights, lacking control units such as gyroscopes, accelerometers, and visual sensors. This limitation hinders precise altitude and attitude control. Future work

should therefore concentrate on developing an advanced FWR, incorporating a well-designed flight control mechanism and feedback systems. Moreover, expanding research into autonomous flight is crucial for the application of FWR-MAVs in various multi-functional scenarios, necessitating the mechatronic integration of specialized hardware control circuits and software tailored to specific needs.

The special work, guided by this thesis's development of an FWR-MAV prototype with flight mode transition, will focus on creating a dedicated control system. This involves two key objectives: firstly, optimizing the vehicle design to enhance control and stability. This optimization will address aspects such as mechanical joint design, component layout, and mass distribution. The challenges identified in Chapter 6, particularly those related to refining the control system, are poised for resolution. Secondly, the research will investigate the aerodynamic performance during the transition from FWR to FW wings. Current gaps in accurate aerodynamic models and unclear flight mechanisms present opportunities for advancement. The goal is to progress from basic remote control to precise attitude control, enabling the integration of FWR and FW for efficient, multi-functional, and versatile applications in the future.

REFERENCES

Alexander, D. E. (2002) *Nature's Flyers: Birds, Insects, and the Biomechanics of Flight*, Johns Hopkins U. Press.

Alexander, R. M. and Bennet-Clark, H. C. (1977) 'Storage of elastic strain energy in muscle and other tissues', *Nature*, 265, pp. 114–117.

Anders, J. B. (2000) 'Biomimetic Flow Control', *AIAA Journal*.

Azhar, M., Campolo, D., Lau, G.K., Hines, L. and Sitti, M. (2013) 'Flapping wings via direct-driving by DC motors', *Proceedings - IEEE International Conference on Robotics and Automation*, pp. 1397–1402. doi: 10.1109/ICRA.2013.6630753.

Baek, S. S., Ma, K. Y. and Fearing, R. S. (2009) 'Efficient resonant drive of flapping-wing robots', *2009 IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS 2009*, pp. 2854–2860. doi: 10.1109/IROS.2009.5354725.

Bhatia, M., Patil, M., Woolsey, C., Stanford, B. and Beran, P. (2014) 'Stabilization of flapping-wing micro-air vehicles in gust environments', *Journal of Guidance, Control, and Dynamics*, 37(2), pp. 592–607. doi: 10.2514/1.59875.

Biewener, A. A. and Patek, S. N. (2018) 'Animal locomotion, second edition', *Animal Locomotion, Second Edition*, pp. 1–223. doi: 10.1093/oso/9780198743156.001.0001.

Bohorquez, F. and Pines, D. (2004) 'Hover performance and swashplate design of a coaxial rotary wing micro air vehicle', *Annual Forum Proceedings - American Helicopter Society*, 1, pp. 629–641.

Bomphrey, R.J., Nakata, T., Henningsson, P. and Lin, H.T. (2016) 'Flight of the dragonflies and damselflies', *Philosophical Transactions of the Royal Society B: Biological Sciences*, 371(1704). doi: 10.1098/rstb.2015.0389.

Bomphrey, R. J. and Godoy-Diana, R. (2018) 'Insect and insect-inspired aerodynamics: unsteadiness, structural mechanics and flight control', *Current Opinion in Insect Science*, 30, pp. 26–32. doi: 10.1016/j.cois.2018.08.003.

Fitchett, B. (2007) *Development and Investigation of a Flapping Rotor for Micro Air Vehicles*. University of Maryland.

Breuer, K. (2019) 'Flight of the RoboBee', *Nature*, 570(7762), pp. 448–449. doi: 10.1038/d41586-019-01964-3.

Camacho, E. A. R. and Henriques, S. T. L. (2017) 'Dynamics and kinematics analysis during take-off and landing in birds', *Advanced Systems of Aeronautical Propulsion*, (October).

Chechetka, S.A., Yu, Y., Tange, M. and Miyako, E. (2017) 'Materially Engineered Artificial Pollinators', *Chem*, 2(2), pp. 224–239. doi: 10.1016/j.chempr.2017.01.008.

Chen, F., Wu, J.H., Zhou, C. and Zhang, Y.L. (2013) 'An automatical matching method applied in kinematics measurement for the flapping rotary wing', *Applied Mechanics and Materials*, 459, pp. 119–124. doi: 10.4028/www.scientific.net/AMM.459.119.

Chen, L., Wu, J., Zhou, C., Hsu, S.J. and Cheng, B. (2018) 'Unsteady aerodynamics of a pitching-flapping-perturbed revolving wing at low Reynolds number', *Physics of Fluids*, 30(5). doi: 10.1063/1.5024925.

Chen, L., Zhou, Y., Zhou, C. and Wu, J. (2022) 'Effects of bore-hole design on the aerodynamics of a flapping rotary wing in forward flight', *Aerospace Science and Technology*, 127, p. 107671. doi: 10.1016/j.ast.2022.107671.

Chen, L., Liu, F. and Qing, Y. (2022) 'Analysis of nonlinear aerodynamic performance and passive deformation of a flexible flapping wing in hover flight', *Journal of Fluids and Structures*, 108(3), p. 103458. doi: 10.1016/j.jfluidstructs.2021.103458.

Chen, L., Wang, L. and Wang, Y. Q. (2022) 'Efficient Fluid–Structure Interaction Model for Twistable Flapping Rotary Wings', *AIAA Journal*, 60(12), pp. 6665–6679. doi: 10.2514/1.J061940.

Chen, L., Yan, W. and Wu, J. (2015) 'Experimental Validation on Lift Increment

of a Flapping Rotary Wing with Boring-hole Design', *Procedia Engineering*, 99, pp. 1543–1547. doi: 10.1016/j.proeng.2014.12.706.

Chen, L., Yang, F. L. and Wang, Y. Q. (2022) 'Analysis of nonlinear aerodynamic performance and passive deformation of a flexible flapping wing in hover flight', *Journal of Fluids and Structures*, 108(3), p. 103458. doi: 10.1016/j.jfluidstructs.2021.103458.

Chen, S., Li, H., Guo, S., Tong, M. and Ji, B. (2018) 'Unsteady aerodynamic model of flexible flapping wing', *Aerospace Science and Technology*, 80, pp. 354–367. doi: 10.1016/j.ast.2018.07.017.

Chen, S., Wang, L., Guo, S., Zhao, C. and Tong, M. (2020) 'A bio-inspired flappingwing rotor of variant frequency driven by ultrasonic motor', *Applied Sciences (Switzerland)*, 10(1), pp. 1–21. doi: 10.3390/app10010412.

Chen, S., Wang, L., He, Y., Tong, M., Pan, Y., Ji, B. and Guo, S. (2022) 'Aerodynamic performance of a flyable flapping wing rotor with passive pitching angle variation', *IEEE Transactions on Industrial Electronics*, vol. 69, no. 9, pp. 9176-9184. doi: 10.1109/TIE.2021.3112964.

Chen, Y., Song, W. and Liu, H. (2010) *Civil Aircraft Design*. Shanghai Jiao Tong University Press.

Chin, D. D. and Lentink, D. (2016) 'Flapping wing aerodynamics: From insects to vertebrates', *Journal of Experimental Biology*, 219(7), pp. 920–932. doi: 10.1242/jeb.042317.

Coleman, D. and Benedict, M. (2015) 'Design , Development and Flight-Testing of a Robotic Hummingbird', *American Helicopter Society 71st Annual Forum*, (May).

Dempsey, M. (2020) 'The stealthy little drones that fly like insects', *BBC News*.

Deng, X., Schenato, L. and Sastry, S. S. (2006) 'Flapping flight for biomimetic robotic insects: Part II - Flight control design', *IEEE Transactions on Robotics*, 22(4), pp. 789–803. doi: 10.1109/TRO.2006.875483.

- Dickinson, M. H., Lehmann, F. O. and Sane, S. P. (1999) 'Wing rotation and the aerodynamic basis of insect flight', *Science*, 284(5422), pp. 1954–1960. doi: 10.1126/science.284.5422.1954.
- Dickson, W. B. and Dickinson, M. H. (2004) 'The effect of advance ratio on the aerodynamics of revolving wings', *Journal of Experimental Biology*, 207(24), pp. 4269–4281. doi: 10.1242/jeb.01266.
- Doman, D. B., Oppenheimer, M. W. and Sigthorsson, D. O. (2010) 'Wingbeat shape modulation for flapping-wing micro-air-vehicle control during hover', *Journal of Guidance, Control, and Dynamics*, 33(3), pp. 724–739. doi: 10.2514/1.47146.
- Dong, X., Li, D., Xiang, J. and Wang, Z. (2020) 'Design and experimental study of a new flapping wing rotor micro aerial vehicle', *Chinese Journal of Aeronautics*, 33(12), pp. 3092–3099. doi: 10.1016/j.cja.2020.04.024.
- Dong, X., Wang, Z., Liu, F., Li, S., Fei, F., Li, D. and Tu, Z. (2022) 'Visual-Inertial Cross Fusion: A Fast and Accurate State Estimation Framework for Micro Flapping Wing Rotors', *Drones* 2022, 6, 90. doi:10.3390/drones6040090
- Du, G. and Sun, M. (2008) 'Effects of unsteady deformation of flapping wing on its aerodynamic forces', *Applied Mathematics and Mechanics (English Edition)*, 29(6), pp. 731–743. doi: 10.1007/s10483-008-0605-9.
- Eldredge, J. D., Toomey, J. and Medina, A. (2010) 'On the roles of chord-wise flexibility in a flapping wing with hovering kinematics', *Journal of Fluid Mechanics*, 659, pp. 94–115. doi: 10.1017/S00222112010002363.
- Ellington, C. P. (1984a) 'The aerodynamics of hovering insect flight. III. Kinematics', *Philosophical Transactions of the Royal Society of London. B, Biological Sciences*, 305(1122), pp. 41–78. doi: 10.1098/rstb.1984.0051.
- Ellington, C. P. (1984b) 'The aerodynamics of hovering insect flight. VI. Lift and power requirements', *Philosophical Transactions of the Royal Society of London. B, Biological Sciences*, 305(1122), pp. 145–181. doi: 10.1098/rstb.1984.0054.

- Ellington, C. P. (1985) 'Power and efficiency of insect flight muscle', *J. Exp. Biol.*, 115, pp. 293–304. doi:10.1242/jeb.115.1.293.
- Ellington, C.P., Van Den Berg, C., Willmott, A.P. and Thomas, A.L.R. (1996) 'Leading-edge vortices in insect flight', *Nature*, 384(6610), pp. 626–630. doi: 10.1038/384626a0.
- Ellington, C. P. (1999) 'The novel aerodynamics of insect flight: Applications to micro-air vehicles', *Journal of Experimental Biology*, 202(23), pp. 3439–3448. doi: 10.1242/jeb.202.23.3439.
- Fujikawa, T., Sato, Y., Makata, Y., Yamashita, T. and Kikuchi, K. (2009) 'Motion analysis of butterfly-style flapping robot for different wing and body design', *2008 IEEE International Conference on Robotics and Biomimetics, ROBIO 2008*, pp. 216–221. doi: 10.1109/ROBIO.2009.4913006.
- Galiński, C. and Zbikowski, R. (2007) 'Some problems of micro air vehicles development', *Bulletin of the Polish Academy of Sciences: Technical Sciences*, 55(1), pp. 91–98.
- Gao, G.L., Song, B.F., Wang, L.G. and Ding, X. (2010) 'Study of opening holes on the wing of flapping-wing MAV and its effect on aerodynamic characteristic', *Shiyan Liuti Lixue/Journal of Experiments in Fluid Mechanics*, pp. 70–73.
- Ghommam, M., Hajj, M.R., Beran, P.S. and Puri, I.K. (2014) 'Role of wing morphing in thrust generation', *Theoretical and Applied Mechanics Letters*, 4(3), p. 032003. doi: 10.1063/2.1403203.
- Godoy-Diana, R. and Thiria, B. (2018) 'On the diverse roles of fluid dynamic drag in animal swimming and flying', *Journal of the Royal Society Interface*, 15(139). doi: 10.1098/rsif.2017.0715.
- Goslow Jr., G. E., Dial, K. P. and Jenkins Jr., F. A. (1990) 'Bird flight: Insights and complications new techniques show that more than the wing participates in flying', *BioScience*, 40(2), pp. 108–115.
- Granlund, K. O., Ol, M. V. and Bernal, L. P. (2013) 'Unsteady pitching flat plates',

Journal of Fluid Mechanics, 733, pp. 1–13. doi: 10.1017/jfm.2013.444.

Grauer, J. A. and Hubbard, J. E. (2009) 'Multibody model of an ornithopter', *Journal of Guidance, Control, and Dynamics*, 32(5), pp. 1675–1679. doi: 10.2514/1.43177.

Guan, Z. and Yu, Y. (2014) 'Aerodynamic mechanism of forces generated by twisting model-wing in bat flapping flight', *Applied Mathematics and Mechanics (English Edition)*, 35(12), pp. 1607–1618. doi: 10.1007/s10483-014-1882-6.

Guo, S., Yang, D., Kummari, K.L. and Huang, Z. (2009) 'A Smart Material Flapping Wing Micro Rotorcraft', in *International Forum On Aeroelasticity and Structural Dynamics*. Seattle, Washington.

Guo, S., Li, H., Zhou, C., Zhang, Y.L., He, Y. and Wu, J.H. (2018) 'Analysis and experiment of a bio-inspired flyable micro flapping wing rotor', *Aerospace Science and Technology*, 79, pp. 506–517. doi: 10.1016/j.ast.2018.06.009.

Guo, S., Li, D. and Wu, J. (2012) 'Theoretical and experimental study of a piezoelectric flapping wing rotor for micro aerial vehicle', *Aerospace Science and Technology*, 23(1), pp. 429–438. doi: 10.1016/j.ast.2011.10.002.

Hassanalain, M. and Abdelkefi, A. (2017) 'Classifications, applications, and design challenges of drones: A review', *Progress in Aerospace Sciences*, 91(November 2016), pp. 99–131. doi: 10.1016/j.paerosci.2017.04.003.

Hawkes, E. W. and Lentink, D. (2016) 'Fruit fly scale robots can hover longer with flapping wings than with spinning wings', *Journal of the Royal Society Interface*, 13(123). doi: 10.1098/rsif.2016.0730.

Heathcote, S. and Gursul, I. (2007) 'Flexible Flapping Airfoil Propulsion at Low Reynolds Numbers', 45(5). doi: 10.2514/1.25431.

Heathcote, S., Wang, Z. and Gursul, I. (2008) 'Effect of spanwise flexibility on flapping wing propulsion', *Journal of Fluids and Structures*, 24(2), pp. 183–199. doi: 10.1016/j.jfluidstructs.2007.08.003.

Hein, T. (2006) 'CBC News In Depth: Science: The world's first flying ornithopter',

CBC News.

Helbling, E. F. and Wood, R. J. (2018) 'A Review of Propulsion, Power, and Control Architectures for Insect-Scale Flapping-Wing Vehicles', *Applied Mechanics Reviews*, 70(1). doi: 10.1115/1.4038795.

Hines, L., Campolo, D. and Sitti, M. (2014) 'Liftoff of a motor-driven, flapping-wing microaerial vehicle capable of resonance', *IEEE Transactions on Robotics*, 30(1), pp. 220–232. doi: 10.1109/TRO.2013.2280057.

Hou, J. and Liu, C. (2020) 'Development Situation and Key Technology Analysis of Cooperative Combat for Unmanned Aerial Vehicle Swarm', *Modern Radar*.

Hou, Z. and Jin, S. (2011) 'A novel data-driven control approach for a class of discrete-time nonlinear systems', *IEEE Transactions on Control Systems Technology*, 19(6), pp. 1549–1558. doi: 10.1109/TCST.2010.2093136.

Hou, Z. S. and Wang, Z. (2013) 'From model-based control to data-driven control: Survey, classification and perspective', *Information Sciences*, 235, pp. 3–35. doi: 10.1016/j.ins.2012.07.014.

Hpo.Ornithopter.Net (2010) 'Successful Flight of the Snowbird'.

Kamakoti, R. and Shyy, W. (2004) 'Fluid-structure interaction for aeroelastic applications', *Progress in Aerospace Sciences*, 40(8), pp. 535–558. doi: 10.1016/j.paerosci.2005.01.001.

Karasek, M., Muijres, F.T., De Wagter, C., Remes, B.D.W. and De Croon, G.C.H.E. (2018) 'A tailless aerial robotic flapper reveals that flies use torque coupling in rapid banked turns', *Science*, 361(6407), pp. 1089–1094. doi: 10.1126/science.aat0350.

Keennon, M., Klingebiel, K., Won, H. and Andriukov, A. (2012) 'Development of the Nano Hummingbird: A Tailless Flapping Wing Micro Air Vehicle', *AIAA Journal*, (January), pp. 1–24.

Khanmirza, E., Yousefi-Koma, A. and Tarvirdizadeh, B. (2012) 'Nonlinear trajectory control of a flapping-wing micro aerial vehicle', *Aircraft Engineering and*

Aerospace Technology, 84(1), pp. 58–65. doi: 10.1108/00022661211194988.

Khosravi, M. and Novinzadeh, A. B. (2021) 'A multi-body control approach for flapping wing micro aerial vehicles', *Aerospace Science and Technology*, 112, p. 106525. doi: 10.1016/j.ast.2021.106525.

Knowles, K., Wilkins, P.C., Ansari, S.A. and Zbikowski, R.W. (2007) 'Integrated Computational and Experimental Studies of Flapping-wing Micro Air Vehicle Aerodynamics', *3rd International Symposium on Integrating CFD and Experiments in Aerodynamics*, (June), pp. 1–15.

Kruyt, J.W., Quicazán-Rubio, E.M., Van Heijst, G.F., Altshuler, D.L. and Lentink, D. (2014) 'Hummingbird wing efficacy depends on aspect ratio and compares with helicopter rotors', *Journal of the Royal Society Interface*, 11(99). doi: 10.1098/rsif.2014.0585.

Lasek, M. and Sibilski, K. (2002) 'Modelling and Simulation of Flapping Wing Control for a Micromechanical Flying Insect (Entomopter)', *AIAA Modeling and Simulation Technologies Conference and Exhibit*, 2002–4973(August). doi: 10.2514/6.2002-4973.

Lau, G.K., Chin, Y.W., Goh, J.T.W. and Wood, R.J. (2014) 'Dipteran-insect-inspired thoracic mechanism with nonlinear stiffness to save inertial power of flapping-wing flight', *IEEE Transactions on Robotics*, 30(5), pp. 1187–1197. doi: 10.1109/TRO.2014.2333112.

Lee, J.S., Kim, J.K., Kim, D.K. and Han, J.H. (2011) 'Longitudinal flight dynamics of bioinspired ornithopter considering fluid-structure interaction', *Journal of Guidance, Control, and Dynamics*, 34(3), pp. 667–677. doi: 10.2514/1.53354.

Lentink, D. (2013) 'Biomimetics: Flying like a fly', *Nature*, 498(7454), pp. 306–307. doi: 10.1038/nature12258.

Lentink, D. and Dickinson, M. H. (2009) 'Rotational accelerations stabilize leading edge vortices on revolving fly wings', *Journal of Experimental Biology*, 212(16), pp. 2705–2719. doi: 10.1242/jeb.022269.

Leys, F., Reynaerts, D. and Vandepitte, D. (2016) 'Outperforming hummingbirds' load-lifting capability with a lightweight hummingbird-like flapping-wing mechanism', *Biology Open*, 5(8), pp. 1052–1060. doi: 10.1242/bio.014357.

Leys, F., Vandepitte, D. and Reynaerts, D. (2015) 'Design of a flapping wing micro air vehicle, based on the Rufous Hummingbird', *2015 IEEE International Conference on Robotics and Biomimetics, IEEE-ROBIO 2015*, pp. 1266–1271. doi: 10.1109/ROBIO.2015.7418945.

Li, D., Guo, S., Di Matteo, N. and Yang, D. (2011) 'Design, experiment and aerodynamic calculation of a flapping wing rotor micro aerial vehicle', *Collection of Technical Papers - AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, (April), pp. 1–9. doi: 10.2514/6.2011-1988.

Li, G. J., Liu, N. S. and Lu, X. Y. (2014) 'Dynamic performance and wake structure of flapping plates with different shapes', *Acta Mechanica Sinica/Lixue Xuebao*, 30(6), pp. 800–808. doi: 10.1007/s10409-014-0112-z.

Li, H., Guo, S., Zhang, Y.L., Zhou, C. and Wu, J.H. (2017) 'Unsteady aerodynamic and optimal kinematic analysis of a micro flapping wing rotor', *Aerospace Science and Technology*, 63, pp. 167–178. doi: 10.1016/j.ast.2016.12.025.

Li, H. and Guo, S. (2018) 'Aerodynamic efficiency of a bioinspired flapping wing rotor at low reynolds number', *Royal Society Open Science*, 5(3). doi: 10.1098/rsos.171307.

Li, Q. and Duan, H. (2012) 'Modeling and Adaptive Control for Flapping-Wing Micro Aerial Vehicle', *Intelligent Computing Technology*. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 269–276.

Liang, B. and Sun, M. (2013) 'Nonlinear flight dynamics and stability of hovering model insects', *Journal of the Royal Society Interface*, 10(85). doi: 10.1098/rsif.2013.0269.

Liani, E., Guo, S. and Allegri, G. (2007) 'Aeroelastic Effect on Flapping Wing Performance', in *48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural*

Dynamics, and Materials Conference.

Liu, H., Ellington, C.P., Kawachi, K., Van Den Berg, C. and Willmott, A.P. (1998) 'A computational fluid dynamic study of hawkmoth hovering', *Journal of Experimental Biology*, 201(4), pp. 461–477.

Loh, K., Cook, M. and Thomasson, P. (2003) 'An investigation into the longitudinal dynamics and control of a flapping wing micro air vehicle at hovering flight', *Aeronautical Journal*, 107(1078), pp. 743–753. doi: 10.1017/s0001924000013506.

Lua, K.B., Lee, Y.J., Lim, T.T. and Yeo, K.S. (2016) 'Aerodynamic effects of elevating motion on hovering rigid hawkmothlike wings', *Journal of Aircraft*, 53(4), pp. 2247–2264. doi: 10.2514/1.J054326.

Ma, K.Y., Chirarattananon, P., Fuller, S.B. and Wood, R.J. (2013) 'Controlled Flight of a Biologically Inspired, Insect-Scale Robot', *Science*, 340(6132), pp. 603–607. doi: 10.1126/science.1231806.

Madangopal, R., Khan, Z. A. and Agrawal, S. K. (2005) 'Biologically inspired design of small flapping wing air vehicles using four-bar mechanisms and quasi-steady aerodynamics', *Journal of Mechanical Design, Transactions of the ASME*, 127(4), pp. 809–816. doi: 10.1115/1.1899690.

Mahjoubi, H. and Byl, K. (2013) 'Modeling synchronous muscle function in insect flight: A bio-inspired approach to force control in flapping-wing MAVs', *Journal of Intelligent and Robotic Systems: Theory and Applications*, 70(1–4), pp. 181–202. doi: 10.1007/s10846-012-9746-x.

Mahjoubi, H. and Byl, K. (2014) 'Dynamics of insect-inspired flapping-wing MAVs: Multibody modeling and flight control simulations', *Proceedings of the American Control Conference*, pp. 3089–3095. doi: 10.1109/ACC.2014.6858637.

Meng, X. and Sun, M. (2011) 'Aerodynamic effects of corrugation in flapping insect wings in forward flight', *Journal of Bionic Engineering*, 8(2), pp. 140–150. doi: 10.1016/S1672-6529(11)60015-2.

- Nachtigall, W. (2018) 'Mechanics and aerodynamics of flight', *Insect Flight*, pp. 1–30. doi: 10.1201/9781351073585.
- Nagai, H. and Isogai, K. (2011) 'Effects of flapping wing kinematics on hovering and forward flight aerodynamics', *AIAA Journal*, 49(8), pp. 1750–1762. doi: 10.2514/1.J050968.
- Nakata, T. and Liu, H. (2012) 'Aerodynamic performance of a hovering hawkmoth with flexible wings: A computational approach', *Proceedings of the Royal Society B: Biological Sciences*, 279(1729), pp. 722–731. doi: 10.1098/rspb.2011.1023.
- Nakata, T., Noda, R. and Liu, H. (2018) 'Effect of twist, camber and spanwise bending on the aerodynamic performance of flapping wings', *Journal of Biomechanical Science and Engineering*, 13(2), pp. 1–11. doi: 10.1299/jbse.17-00618.
- Nan, Y., Karasek, M., Lalami, M.E. and Andre, P. (2017) 'Experimental optimization of wing shape for a hummingbird-like flapping wing micro air vehicle', *Bioinspiration and Biomimetics*, 12(2): 026010. doi: 10.1088/1748-3190/aa5c9e.
- Nguyen, Q.-V. and Chan, W. L. (2019) 'Development and Flight Performance of a Biological-inspired Tailless Flapping Wing Micro Air Vehicle with Wing Stroke Plane Modulation', *Bioinspiration & Biomimetics ACCEPTED*, pp. 0–12. doi: 10.1088/1748-3190/aaefa0.
- Norberg, U. M. (1990) *Vertebrate flight: mechanics, physiology, morphology, ecology and evolution*. Springer, Berlin, Heidelberg.
- Orlowski, C. T. and Girard, A. R. (2011) 'Modeling and simulation of nonlinear dynamics of flapping wing micro air vehicles', *AIAA Journal*, 49(5), pp. 969–981. doi: 10.2514/1.J050649.
- Petricca, L., Ohlckers, P. and Grinde, C. (2011) 'Micro- and nano-air vehicles: State of the art', *International Journal of Aerospace Engineering*, 2011. doi: 10.1155/2011/214549.
- Pfeiffer, A.T., Lee, J.S., Han, J.H. and Baier, H. (2010) 'Ornithopter Flight

Simulation Based on Flexible Multi-Body Dynamics', *Journal of Bionic Engineering*, 7(1), pp. 102–111. doi: 10.1016/S1672-6529(09)60189-X.

Phan, H. V. and Park, H. C. (2018) 'Wing inertia as a cause of aerodynamically uneconomical flight with high angles of attack in hovering insects', *Journal of Experimental Biology*, 221(19). doi: 10.1242/jeb.187369.

Phan, H. V. and Park, H. C. (2019) 'Insect-inspired, tailless, hover-capable flapping-wing robots: Recent progress, challenges, and future directions', *Progress in Aerospace Sciences*, 111(March), p. 100573. doi: 10.1016/j.paerosci.2019.100573.

Phan, H. V. and Park, H. C. (2020) 'Mechanisms of collision recovery in flying beetles and flapping-wing robots', *Science*, 370(6521), pp. 1214–1219. doi: 10.1126/science.abd3285.

Phillips, N., Knowles, K. and Bomphrey, R. J. (2015) 'The effect of aspect ratio on the leading-edge vortex over an insect-like flapping wing', *Bioinspiration and Biomimetics*, 10(5), p. 56020. doi: 10.1088/1748-3190/10/5/056020.

Pines, D. J. and Bohorquez, F. (2006) 'Challenges facing future micro-air-vehicle development', *Journal of Aircraft*, 43(2), pp. 290–305. doi: 10.2514/1.4922.

Ramesh, K., Gopalarathnam, A., Edwards, J.R., Ol, M. V. and Granlund, K. (2013) 'An unsteady airfoil theory applied to pitching motions validated against experiment and computation', *Theoretical and Computational Fluid Dynamics*, 27(6), pp. 843–864. doi: 10.1007/s00162-012-0292-8.

Rayner, J. M. V. (1979) 'A New Approach to Animal Flight Mechanics', *Journal of Experimental Biology*, 80(1), pp. 17–54.

Rayner, J. M. V. (1988) 'Form and Function in Avian Flight', *Current Ornithology*, pp. 1–66. doi: 10.1007/978-1-4615-6787-5_1.

Reichhardt, T. (2014) *Birds Make Landing on a Wire Look Easy. Now Try It With a Drone.*, AIRSPACEMAG.COM.

Ren, H., Wang, X., Li, X. and Chen, Y. (2013) 'Effects of Dragonfly Wing Structure

on the Dynamic Performances', *Journal of Bionic Engineering*, 10(1), pp. 28–38. doi: 10.1016/S1672-6529(13)60196-1.

Roberts, L. J., Bruck, H. A. and Gupta, S. K. (2016) 'Modeling of dive maneuvers in flapping wing unmanned aerial vehicles', *SSRR 2015 - 2015 IEEE International Symposium on Safety, Security, and Rescue Robotics*. doi: 10.1109/SSRR.2015.7443017.

Roshanbin, A., Altartouri, H., Karásek, M. and Preumont, A. (2017) 'COLIBRI: A hovering flapping twin-wing robot', *International Journal of Micro Air Vehicles*, 9(4), pp. 270–282. doi: 10.1177/1756829317695563.

Sachs, G. (2016) 'Comparison of power requirements: Flapping vs. fixed wing vehicles', *Aerospace*, 3(4). doi: 10.3390/aerospace3040031.

Salami, E., Ward, T.A., Montazer, E. and Ghazali, N.N.N. (2019) 'A review of aerodynamic studies on dragonfly flight', *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 233(18), pp. 6519–6537. doi: 10.1177/0954406219861133.

Salami, E., Montazer, E., Ward, T.A., Nik Ghazali, N.N. and Badruddin, I.A. (2022) 'Aerodynamic Performance of a Dragonfly-Inspired Tandem Wing System for a Biomimetic Micro Air Vehicle', *Frontiers in Bioengineering and Biotechnology*, 10(May), pp. 1–12. doi: 10.3389/fbioe.2022.787220.

Sane, S. P. (2003) 'The aerodynamics of insect flight', *Journal of Experimental Biology*, 206(23), pp. 4191–4208. doi: 10.1242/jeb.00663.

Sane, S. P. and Dickinson, M. H. (2001) 'The control of flight force by a flapping wing: Lift and drag production', *Journal of Experimental Biology*, 204(15), pp. 2607–2626.

Sane, S. P. and Dickinson, M. H. (2002) 'The aerodynamic effects of wing rotation and a revised quasi-steady model of flapping flight', *Journal of Experimental Biology*, 205(8), pp. 1087–1096. doi: 10.1242/jeb.205.8.1087.

Shahzad, A., Tian, F.B., Young, J. and Lai, J.C.S. (2016) 'Effects of wing shape,

aspect ratio and deviation angle on aerodynamic performance of flapping wings in hover', *Physics of Fluids*, 28(11). doi: 10.1063/1.4964928.

Shahzad, A., Tian, F.B., Young, J. and Lai, J.C.S. (2018) 'Effects of flexibility on the hovering performance of flapping wings with different shapes and aspect ratios', *Journal of Fluids and Structures*, 81, pp. 69–96. doi: 10.1016/j.jfluidstructs.2018.04.019.

Shao, H., Li, D., Kan, Z., Li, H., Yuan, D. and Xiang, J. (2021) 'Influence of wing camber on aerodynamic performance of flapping wing rotor', *Aerospace Science and Technology*, 113, p. 106732. doi: 10.1016/j.ast.2021.106732.

Shen, Y., Ge, W. and Miao, P. (2021) 'Multibody-Dynamic Modeling and Stability Analysis for a Bird-scale Flapping-wing Aerial Vehicle', *Journal of Intelligent and Robotic Systems: Theory and Applications*, 103(1). doi: 10.1007/s10846-021-01436-9.

Shyy, W., Lian, Y., Tang, J., Viieru, D. and Liu, H. (2011) *Aerodynamics of Low Reynolds Number Flyers More information*, Cambridge University Press.

Spedding, G. R. and Maxworthy, T. (1986) 'The generation of circulation and lift in a rigid two-dimensional fling', *Journal of Fluid Mechanics*, 165, pp. 247–272. doi: 10.1017/S0022112086003087.

Stanford, B., Beran, P. and Patil, M. (2013) 'Optimal flapping-wing vehicle dynamics via floquet multiplier sensitivities', *Journal of Guidance, Control, and Dynamics*, 36(2), pp. 454–466. doi: 10.2514/1.57213.

Steltz, E., Avadhanula, S. and Fearing, R. S. (2007) 'High lift force with 275 Hz wing beat in MFI', *IEEE International Conference on Intelligent Robots and Systems*, pp. 3987–3992. doi: 10.1109/IROS.2007.4399068.

Sun, X., Zhao, L. and Jiao, Z. (2017) 'Analyses and simulations of propulsion mechanisms for flapping wings with the extension of Undulate Propulsion Theory', *CGNCC 2016 - 2016 IEEE Chinese Guidance, Navigation and Control Conference*, pp. 1794–1799. doi: 10.1109/CGNCC.2016.7829063.

- Tahmasian, S., Woolsey, C. A. and Taha, H. E. (2014) 'Longitudinal flight control of flapping wing micro air vehicles', *AIAA Guidance, Navigation, and Control Conference*, (January), pp. 1–13. doi: 10.2514/6.2014-1470.
- Tantanawat, T. and Kota, S. (2007) 'Design of compliant mechanisms for minimizing input power in dynamic applications', *Journal of Mechanical Design, Transactions of the ASME*, 129(10), pp. 1064–1075. doi: 10.1115/1.2756086.
- Taylor, G. K., Nudds, R. L. and Thomas, A. L. R. (2003) 'Flying and swimming animals cruise at a Strouhal number tuned for high power efficiency', *Nature*, 425(6959),. doi: doi:10.1038/nature02000.
- Tobalske, B. W. and Dial, K. P. (1996) 'Flight kinematics of black-billed magpies and pigeons over a wide range of speeds', *Journal of Experimental Biology*, 199(2), pp. 263–280.
- Triantafyllou, G. S., Triantafyllou, M. S. and Grosenbaugh, M. A. (1993) 'Optimal thrust development in oscillating foils with application to fish propulsion', *Journal of Fluids and Structures*, pp. 205–224. doi: 10.1006/jfls.1993.1012.
- Truong, T.Q., Phan, V.H., Park, H.C. and Ko, J.H. (2013) 'Effect of wing twisting on aerodynamic performance of flapping wing system', *AIAA Journal*, 51(7), pp. 1612–1620. doi: 10.2514/1.J051831.
- Tu, Z., Fei, F. and Deng, X. (2020) 'Untethered Flight of an At-Scale Dual-Motor Hummingbird Robot with Bio-Inspired Decoupled Wings', *IEEE Robotics and Automation Letters*, 5(3), pp. 4194–4201. doi: 10.1109/LRA.2020.2974717.
- Usherwood, J. R. and Lehmann, F. O. (2008) 'Phasing of dragonfly wings can improve aerodynamic efficiency by removing swirl', *Journal of the Royal Society Interface*, 5(28), pp. 1303–1307. doi: 10.1098/rsif.2008.0124.
- Vandenbergh, N., Zhang, J. and Childress, S. (2004) 'Symmetry breaking leads to forward flapping flight', *Journal of Fluid Mechanics*, 506, pp. 147–155. doi: 10.1017/S0022112004008468.
- Vanella, M., Fitzgerald, T., Preidikman, S., Balaras, E. and Balachandran, B.

(2009) 'Influence of flexibility on the aerodynamic performance of a hovering wing', pp. 95–105. doi: 10.1242/jeb.016428.

De Wagter, C., Tijmons, S., Remes, B.D.W. and De Croon, G.C.H.E. (2014) 'Autonomous flight of a 20-gram Flapping Wing MAV with a 4-gram onboard stereo vision system', *Proceedings - IEEE International Conference on Robotics and Automation*, pp. 4982–4987. doi: 10.1109/ICRA.2014.6907589.

Wang, D., Wu, J. and Zhang, Y. (2013) 'Aerodynamics on flapping rotary wing in low reynolds number', *2013 International Powered Lift Conference*, (37), pp. 1–14. doi: 10.2514/6.2013-4382.

Wang, D., Wu, J. and Zhang, Y. (2018) 'Effects of geometric parameters on Flapping rotary wings at low Reynolds numbers', *AIAA Journal*, 56(4), pp. 1372–1387. doi: 10.2514/1.J055994.

Wang, H., Zeng, L., Liu, H. and Yin, C. (2003) 'Measuring wing kinematics, flight trajectory and body attitude during forward flight and turning maneuvers in dragonflies', *Journal of Experimental Biology*, 206(4), pp. 745–757. doi: 10.1242/jeb.00183.

Wang, Q., Goosen, J. F. L. and Keulen, F. van (2017) 'An efficient fluid–structure interaction model for optimizing twistable flapping wings', *Journal of Fluids and Structures*, 73, pp. 82–99. doi: 10.1016/j.jfluidstructs.2017.06.006.

Wang, Z. J. (2004) 'The role of drag in insect hovering', *Journal of Experimental Biology*, 207(23), pp. 4147–4155. doi: 10.1242/jeb.01239.

Wang, Z. J., Birch, J. M. and Dickinson, M. H. (2004) 'Unsteady forces and flows in low Reynolds number hovering flight: Two-dimensional computations vs robotic wing experiments', *Journal of Experimental Biology*, 207(3), pp. 449–460. doi: 10.1242/jeb.00739.

Ward, T.A., Rezadad, M., Fearday, C.J. and Viyapuri, R. (2015) 'A Review of Biomimetic Air Vehicle Research : 1984-2014', *International Journal of Micro Air Vehicles*, 7(3), pp. 375–394. doi: 10.1260/1756-8293.7.3.375.

- Weis Fogh, T. (1973) 'Quick estimates of flight fitness in hovering animals, including novel mechanisms for lift production', *Journal of Experimental Biology*, 59(1), pp. 169–230.
- Wood, R. J. (2007) 'Liftoff of a 60mg flapping-wing MAV', *IEEE International Conference on Intelligent Robots and Systems*, pp. 1889–1894. doi: 10.1109/IROS.2007.4399502.
- Wootton, R. (2020) 'The geometry and mechanics of insect wing deformations in flight: A modelling approach', *Insects*, 11(7), pp. 1–19. doi: 10.3390/insects11070446.
- Wu, J., Chen, L., Zhou, C., Hsu, S.J. and Cheng, B. (2019) 'Aerodynamics of a flapping-perturbed revolving wing', *AIAA Journal*, 57(9), pp. 3728–3743. doi: 10.2514/1.J056584.
- Wu, J., Yan, H., Zhou, C. and Zhang, Y. (2021) 'Unsteady aerodynamics of a micro flapping rotary wing in forward flight', *Aerospace Science and Technology*, 111, p. 106530. doi: 10.1016/j.ast.2021.106530.
- Wu, J. H. and Sun, M. (2012) 'Floquet stability analysis of the longitudinal dynamics of two hovering model insects', *Journal of the Royal Society Interface*, 9(74), pp. 2033–2046. doi: 10.1098/rsif.2012.0072.
- Wu, J., Qiu, J. and Zhang, Y. (2017) 'Automated Kinematics Measurement and Aerodynamics of a Bioinspired Flapping Rotary Wing', *Journal of Bionic Engineering*, 14(4), pp. 726–737. doi: 10.1016/S1672-6529(16)60438-9.
- Wu, J., Wang, D. and Zhang, Y. (2015) 'Aerodynamic analysis of a flapping rotary wing at a low reynolds number', *AIAA Journal*, 53(10), pp. 2951–2966. doi: 10.2514/1.J053845.
- Wu, J., Zhou, C. and Zhang, Y. (2012) 'A novel design in micro-air-vehicle: Flapping rotary wings', *Applied Mechanics and Materials*, 232, pp. 189–193. doi: 10.4028/www.scientific.net/AMM.232.189.
- Wu, J., Zhou, C. and Zhang, Y. (2016) 'Aerodynamic power efficiency comparison

of various micro-Air-vehicle layouts in hovering flight', *AIAA Journal*, 55(4), pp. 1265–1278. doi: 10.2514/1.J055221.

Wu, P., Ifju, P., Stanford, B., Sällström, E., Ukeiley, L., Love, R. and Lind, R. (2009) 'A multidisciplinary experimental study of flapping wing aeroelasticity in thrust production', in *Collection of Technical Papers - AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, pp. 1–19. doi: 10.2514/6.2009-2413.

Wu, P., Ifju, P. and Stanford, B. (2010) 'Flapping wing structural deformation and thrust correlation study with flexible membrane wings', *AIAA Journal*, 48(9), pp. 2111–2122. doi: 10.2514/1.J050310.

Yang, W., Xu, J. and Xuan, J. (2019) 'Experimental Study on the Stiffness and Shape Layout of Flapping Wing', *IOP Conference Series: Materials Science and Engineering*, 686(1). doi: 10.1088/1757-899X/686/1/012029.

Yi, S., Li, D., Jiang, J., Xiang, J. and Wei, X. (2017) 'Design and Experimental Study of a New Flapping Wing Rotor Micro Aerial Vehicle.', *IEEE international conference on unmanned systems (ICUS)*, pp. 29-33. doi: 10.1109/ICUS.2017.8278312

Young, J. (2012) 'Details of insect wing design and deformation enhance aerodynamic function and flight efficiency', *Science*, 1549(2009). doi: 10.1126/science.1175928.

Zhang, H., Zhou, J., Sun, Q., Guerrero, J.M. and Ma, D. (2017) 'Data-Driven Control for Interlinked AC/DC Microgrids Via Model-Free Adaptive Control and Dual-Droop Control', *IEEE Transactions on Smart Grid*, 8(2), pp. 557–571. doi: 10.1109/TSG.2015.2500269.

Zhang, J. and Deng, X. (2017) 'Resonance Principle for the Design of Flapping Wing Micro Air Vehicles', *IEEE Transactions on Robotics*, 33(1), pp. 183–197. doi: 10.1109/TRO.2016.2626457.

Zhao, L., Huang, Q., Deng, X. and Sane, S.P. (2010) 'Aerodynamic effects of flexibility in flapping wings', *Journal of the Royal Society Interface*, 7(44), pp. 485–

497. doi: 10.1098/rsif.2009.0200.

Zhao, L. and Deng, X. (2009) 'Power distribution in the hovering flight of the hawk moth *Manduca sexta*', *Bioinspiration and Biomimetics*, 4(4). doi: 10.1088/1748-3182/4/4/046003.

Zheng, L., Hedrick, T. and Mittal, R. (2013) 'A comparative study of the hovering efficiency of flapping and revolving wings', *Bioinspiration and Biomimetics*, 8(3). doi: 10.1088/1748-3182/8/3/036001.

Zhou, C., Wu, J., Guo, S. and Li, D. (2014) 'Experimental study on the lift generated by a flapping rotary wing applied in a micro air vehicle', *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, 228(11), pp. 2083–2093. doi: 10.1177/0954410013512761.

Zhou, C., Zhang, Y. and Wu, J. (2018) 'Unsteady Aerodynamic Forces and Power Consumption of a Micro Flapping Rotary Wing in Hovering Flight', *Journal of Bionic Engineering*, 15(2), pp. 298–312. doi: 10.1007/s42235-018-0023-y.

Zhu, Z., Zhao, J., He, Y., Guo, S., Chen, S. and Ji, B. (2022) 'Aerodynamic analysis of insect-like flapping wings in fan-sweep and parallel motions with the slit effect', *Biomimetic Intelligence and Robotics*, 2(2), p. 100046. doi: 10.1016/j.birob.2022.100046.