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Literature Study on Foldable Flapping Wing Mechanisms

Prof. T Subash[1], Yusra Touseef[2], D Yashaswini Patel[3], Harshan Gowda H N[4], Soniya K S[5]

Assistant Professor, Department of Aeronautical Engineering, East West College of Engineering, Bangalore, India[1]

Students, Department of Aeronautical Engineering, East West College of Engineering, Bangalore, India[2-5]

Abstract: Scientists are looking to nature for inspiration in their hunt for effective and adaptable robotic systems, particularly in the form of bird flight. In biomimetic robotics, foldable flapping wing systems have become a promising field with advantages in mobility, agility, and energy efficiency. The main topics of this paper's thorough literature assessment are the design ideas, manufacturing methods, and applications of foldable flapping wing systems. The most recent developments in control techniques for coordinating wing motion and attaining stable flight are covered in this study. This paper intends to provide insights into the state-of-the-art, identify research gaps, and suggest options for further inquiry into foldable flapping wing mechanics for biomimetic robotics by integrating findings from various sources.

Keywords: Foldable flapping wing, flapping wing mechanism, biomimicry, bat wings.

I. INTRODUCTION

A. Micro Air Vehicles

The term "micro air vehicle" (MAV) defines a type of remotely piloted aircraft (or UAV) that can be created utilizing cutting-edge technology that is much smaller than conventional unmanned vehicles. Currently, the desired dimension for MAVs is about 15 centimeters or six inches, and the development of aircraft the size of insects is supposedly anticipated soon. One of the motivating reasons is the possibility of military usage, even if MAVs are also employed in commerce, science, law enforcement, and mapping.

These platforms represent a significant leap in robotics due to their mechanical simplicity, agility, and ability to reach remote or inaccessible regions. Additionally, equipping MAVs with the right sensor suites will make them an effective aerial instrument for a variety of uses, including mining, public safety monitoring, infrastructure inspection, and search and rescue operations. When compared to traditional procedures, MAVs have the profound potential to significantly reduce the hazards to human life, expedite the process, and boost overall efficiency.

The integration of aerial robots to work closely with human operators is a powerful incentive to create dependable autonomous systems that can function safely in a deployed environment. Therefore, reliability in many critical enabling technologies—such as localization, navigation, and planning—remains necessary to create safe and reliable autonomous aerial systems.

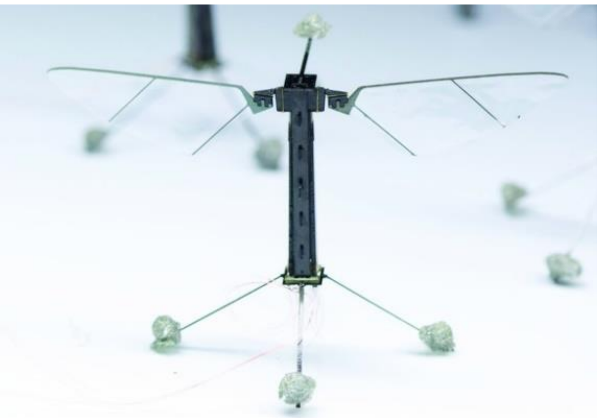

Fig. 1 A Robot Bee MAV

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B. Flapping Mechanism in MAVs

Nature's fliers are everywhere, with over 10,000 flying birds and bats and about a million different species of winged insects. Given that not enough investigative instruments were available until recently (e.g. particle image velocimetry, computational fluid dynamics, real-time operating systems, etc.), study on flapping flight has been considerably hampered. The advent of these instruments and the corresponding progress in comprehending flapping light physics have generated curiosity over the creation of flapping aerial robots that can maneuver within enclosed spaces.

Flapping wing MAVs offer the potential for decreased detectability (due to reduced size and possibly reduced noise) and the ability to hover. Because of this, applications for MAVs are wide-ranging and include surveillance, reconnaissance, or even search and rescue. A novel concept aircraft that imitates the flight characteristics of insects or birds is called the Micro-Fly-Winged Aircraft (FMAV). The primary distinction between tiny flap-wing and fixed-wing and rotor-wing aircraft is that the former combines lifting, hovering, and propulsion tasks into a flapping wing system that is highly flexible and capable of long-distance flight on minimal energy. Flapping wings have advantages over fixed and rotor wings, according to studies.

C. Bird Aerodynamics

To fly, birds must have wings. Unlike airplanes they must have moving wings, i.e., they must have either flapping or, in one exceptional case (the hummingbird), even oscillating wings. The basic structure of a bird's wing resembles the human hand, only the proportions of the bones are different, as much as they are different in every bird species. The hand section of the wing provides the main dynamic control for the bird. The actual shape of the bird wing is made of two organized sets of feathers – in the first set are the flight feathers anchored in the digits (primaries) and the ulna (secondaries). There are also three sets of the so-called coverts which act as a protective cover for all or part of the folded primaries and secondaries.

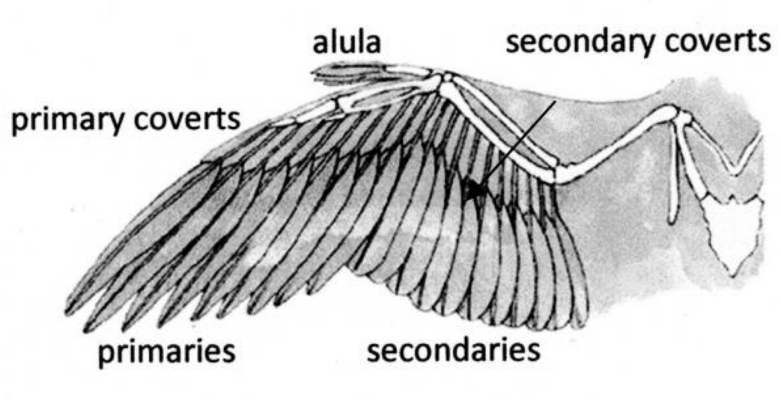

Fig. 2 Flight Feathers

Primaries are connected to the bird's fingers and are the longest and narrowest of the outer feathers (the remiges). They can be individually rotated. These feathers are the main source of thrust, mostly generated on the downstroke of flapping flight. On the upstroke the primaries are separated and rotated, reducing air resistance while still helping to provide some thrust. Remiges on the wingtips of large soaring birds like condors or vultures also allow for spreading the feathers, thus reducing the creation of wingtip vortices.

Secondaries are connected to the ulna. They remain close together in flight (they cannot be individually separated like the primaries) and help to provide lift by creating the airfoil shape of the bird's wing. Secondaries are usually shorter and broader than primaries.

The alula feathers are not flight feathers strictly; however, they are very useful in slow flight. Attached to the bird's "thumb", they lie normally flush against the leading edge of the wing and detach only at higher angles of attack creating a gap between the alula and the rest of the wing (compared with slats on airplane wings). Birds can thus avoid stalling at low speeds or at landing.

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To fly, wings impart downward momentum to the surrounding air and obtain lift by reaction. This is Newton's 3rd Law, which says that action and reaction are equal and opposite to each other. The lift force, which counterbalances the weight, is obtained from Newton's 2nd Law. To obtain the downward momentum, we have to know the downward component of the velocity deflected by the wing and the mass flow which is proportional to the air density, the wing area, and the downward component of the velocity. This velocity component depends on the flight speed and the angle of attack.

The mass flow due to the deflected wing depends on the wing area, wing curvature, and in birds also on various lift-increasing manipulations with the feathers. However, in principle, lift depends primarily on the angle of attack. With the only exception of a hummingbird, birds generate lift and thrust by flapping their wings. This is a complex unsteady and three-dimensional motion of the wings, changing at every instant with the new position of the wings.

The aerodynamic analysis of bird flight was usually based on the quasi-steady assumption, according to which all instantaneous forces on a flapping wing in unsteady motion are assumed to be those corresponding to steady motion at the same instantaneous velocity and attitude. This assumption may be misleading (as is the case when dealing with insect flight) and it is considered that even the aerodynamics of the bird flight is unsteady.

Of course, wings not only generate lift and thrust, but they also cause drag as well. Optimally designed wings have to bring the air from upstream to downstream with as little loss of momentum, i.e. loss of drag, as possible and at the highest lift possible. Lift and drag are two components of the resulting aerodynamic force acting on the wing. The actual size of the components of the resulting aerodynamic force on vertical and horizontal axes depends primarily on the argument and magnitude of the wingbeat velocity.

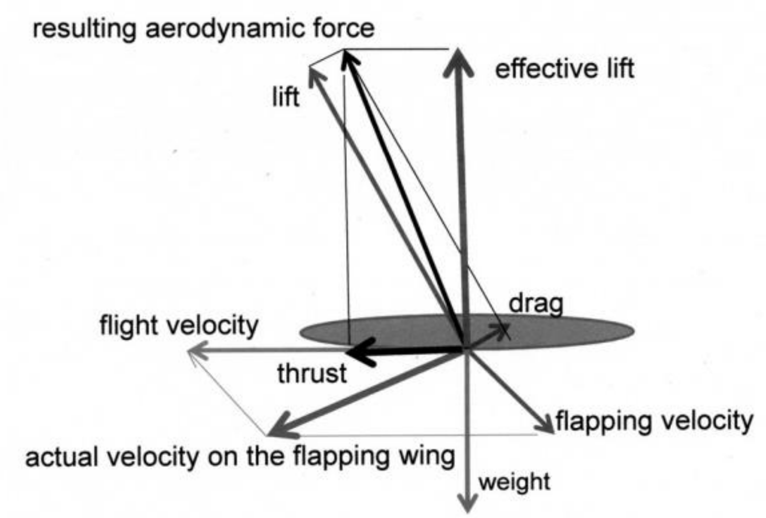

Fig. 3 Aerodynamic Forces on Flapping Wing

D. Bat Flight

Bats exhibit extraordinary flight capabilities owing to their unique wing structure. A bat’s wing consists of an upper arm, forearm, thumb, and digits, very much like a human hand, but the relative lengths of the bones vary significantly - the digits in particular are longer than the forearm. The bones are elongated, slender, and flexible to support and manipulate a thin compliant wing membrane that extends between the hand and the body and forms the lifting surface. The wing has up to 25 actively controlled joints and 34 degrees of freedom which allow them to attain complex spatial planforms and generate a wider range of aerodynamic forces, thus providing higher maneuverability (Bahlman et al. (2013)). The most distinctive feature of the batwing is the ability to fold and unfold the wing in flight during the upstroke and downstroke respectively.

The degree to which upstroke wing folding occurs in a flying vertebrate is expressed as the span ratio, the ratio of upstroke wingspan to downstroke wingspan. In bats, this ratio lies between 0.3-0.5, much lower in comparison to 0.9 in Hummingbirds and 0.6-0.8 in birds, which shows the pronounced significance of the folding action in bats compared to other flying creatures. Folding the wings towards the body during the upstroke helps significantly reduce aerodynamic drag and inertial costs of flapping and mitigate the effect of negative lift, thus giving bats an energy-efficient flight.

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Bat wings are unique among extant actively flying animals, formed by a thin skin membrane stretched by elongated arm and hand bones. The wing is divided into sections as defined by the bone elements. The inner wing, proximal to the first and fifth digits, is formed by the propatagium and the plagiopatagium (Fig 1.4).

The hand wing, the dactylopatagium (d.), is subdivided into d. major, d. medius, d. minus and d. brevis (Fig 1.4). Compared with birds and insects, bat wings are relatively compliant and have a wider range of possible morphological adjustments, implying an ability to control wing morphology according to aerodynamic demands. At the same time, the construction implies several 'design' problems, such as how to keep the membrane taut to minimize the drag of the wing.

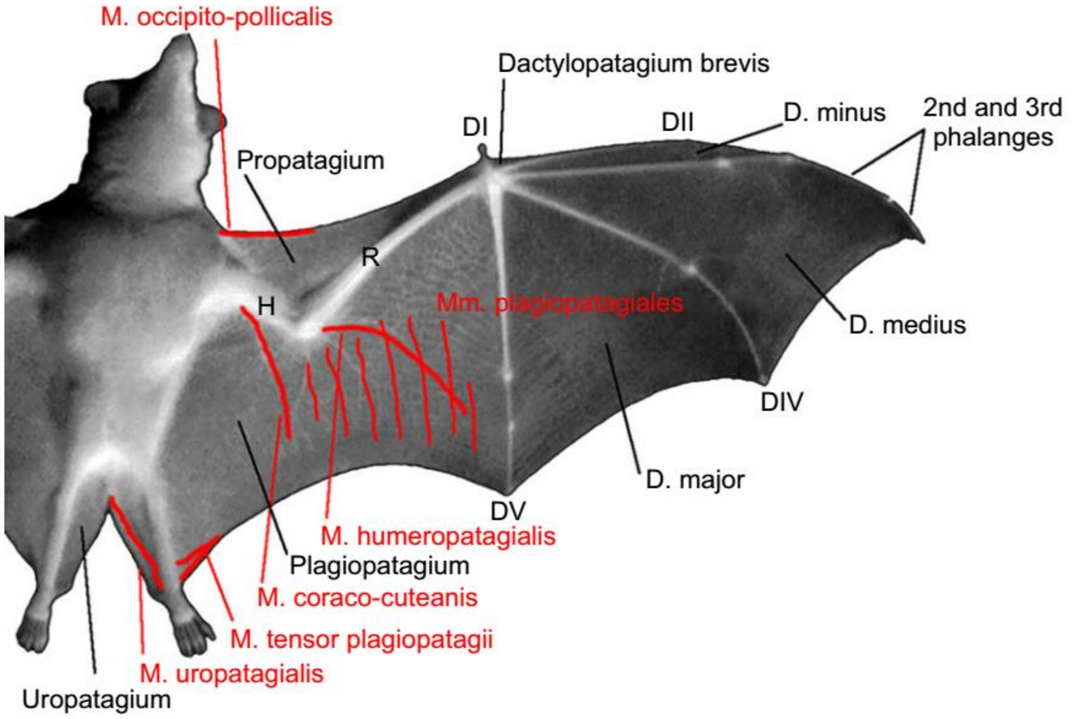

Fig. 4 Morphology of the bat wing. Humerus (H), radius (R), the digits (DI–DV), and the different membranes, propataguim, plagiopatagium, dactylopatagium (d. brevis, d. minus, d. medius, d. major), uropatagium and many muscles (red) associated with tensioning of the wing membrane are indicated.

II. LITERATURE REVIEW

A. Design and Development of a Folding Mechanism for Bat-like Bioinspired Wing by Radha Lahoti (radhammlahoti@gmail.com) [Department of Mechanical Engineering, IIT Bombay, Maharashtra, India 400076]; Abhijit Gogulapati (abhijit@aero.iitb.ac.in) [Department of Aerospace Engineering, IIT Bombay, Maharashtra, India 400076]; Prasanna Gandhi (gandhi@iitb.ac.in) [Department of Mechanical Engineering, IIT Bombay, Maharashtra, India 400076]

The study paper provides a step-by-step process for creating and testing a brand-new, batwing-inspired single-degree-of-freedom wing folding mechanism. The authors set out to create a device that would mimic a bat's planar wing folding. To design the cross-sections of the bone links, they explain the analytical process for the synthesis of the folding mechanism and the assessment of aerodynamic loads on the wing bone framework.

The paper describes the design of a one-degree-of-freedom mechanism that uses a four-bar linkage to drive the wing digits and a slider crank arrangement. The bone dimensions of the bat, Rousettus aegyptiacus, were used to determine the lengths of the major links, and the requisite angular positions of each joint in the fully-folded and fully-extended positions.

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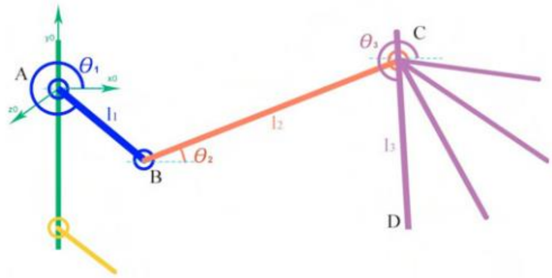

Fig. 5 Folding mechanism (here numbers 1, 2, and 3 represent the sub-parts of parent links wherever applicable)

To determine how much force the wing would need to produce and support, an aerodynamic analysis was carried out. An approximation of the forces was determined by the study using the stable aerodynamics model, and the developed wing was meant to withstand those estimated forces. For the static force analysis of load-bearing links, the researchers employed Bernoulli beam theory, and for each of the main load-bearing links, they conducted stress analysis. Based on the findings of the static force analysis, it was determined that the minimal safety factor was 5.117 and that the cross-sections of the bone links were safe under bending and torsional stresses.

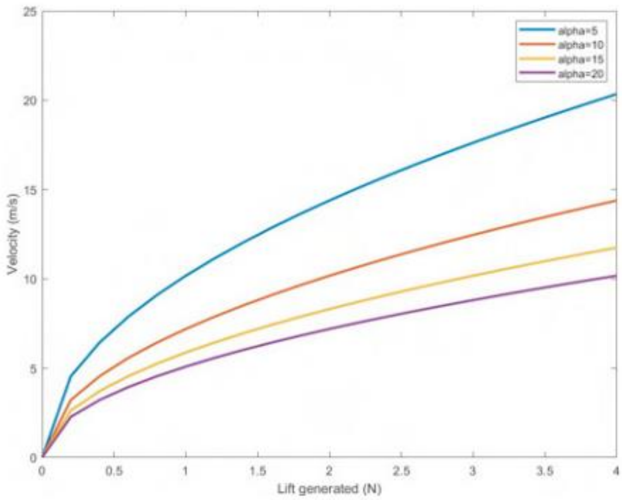

Fig. 6 Velocity vs Lift generated plot for Static Failure Analysis

The procedure of creating a functional prototype with 3D printing for the wing membrane and latex rubber sheet for the bone connections is also covered in the research article. The actuation mechanism utilizing an Arduino UNO microcontroller, an A4988 stepper driver, and a stepper motor connected with a lead screw are described in depth in the paper. The kinematic configuration angles of the biological batwing, planned model, and manufactured prototype are compared by the authors. The research concludes by stating that more work may be done to create a new breed of highly agile and energy-efficient UAVs with flapping wings that resemble bats.

Fig. 7 Prototype with the Latex Membrane attached

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B. Lift Study of a Flapping MAV Wing Design Based on Bat Wings by S Suhaimi, S Shuib [Faculty of Mechanical Engineering, UniversitiTeknologi MARA Shah Alam, 40450, Shah Alam, Selangor, Malaysia]; A H Kadarman [School of Aerospace Engineering, UniversitiSains Malaysia, Engineering Campus, 14300, NibongTebal, Pulau Pinang, Malaysia]; H Yusoff [Faculty of Mechanical Engineering, UniversitiTeknologi MARA, CawanganPulau Pinang, 13500, PermatangPauh, Pulau Pinang, Malaysia]

Based on the structure of bat wings, the study report examined the design and functionality of a micro air vehicle (MAV) wing. To tackle a mechanical difficulty, the study's goal was to harness bio-inspiration to create a wing for the MAVs. A flat wing with the margin shape of a batwing was produced using the wing model, which was developed by in vivo observation of a batwing's shape. At a wind speed of 4 m/s, the wing's lift was examined at a flapping angle of 55 ° and an angle of attack ranging from 0 ° to 35 °. A subsonic wind tunnel was used for the experimental validation, and ANSYS V1.6 software was used for the simulation.

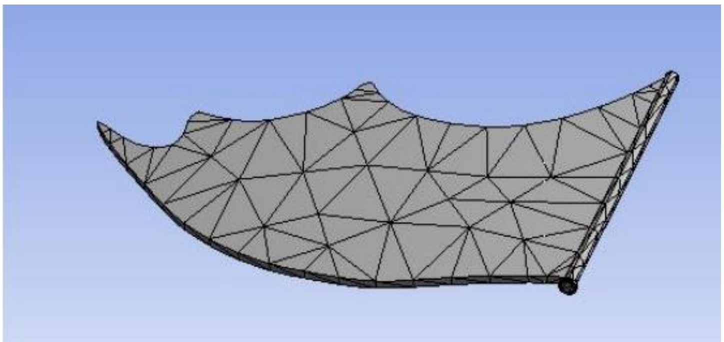

Fig. 8 The Generated Wing Mesh

According to the study, the wing has a maximum lift coefficient (C_{Lmax}) of 3.2 and a stall angle of 25°. With a 0.2% difference at the lowest point and a 5% difference at the greatest, the results also showed that there was a slight discrepancy between the simulation and the observation data. This implied that the simulation model made sense and could be applied to the design of wings in the future.

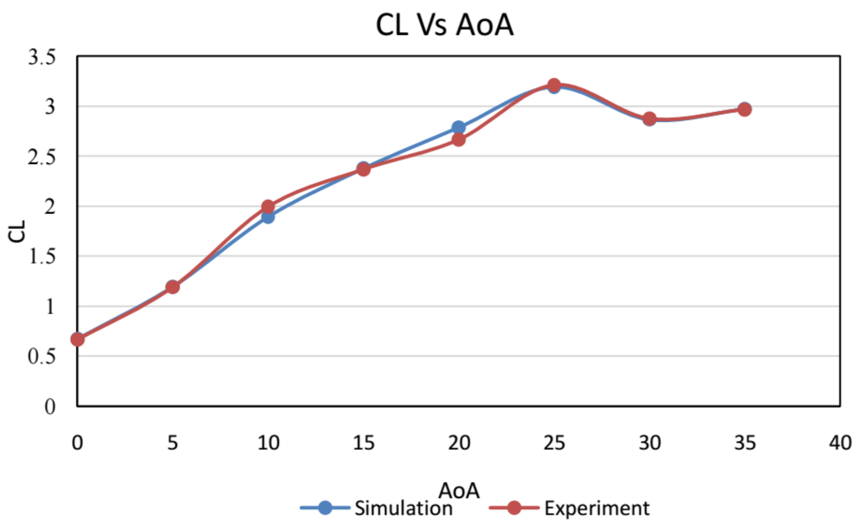

Fig. 9 Lift Generation over the different Angles of Attack for both Simulation and Experimental Study

The study solved the mechanical difficulty of MAV wing design by using bio-inspiration, a design ideation process, to develop the wing model. Creating a design that is influenced by the forms and functions found in nature is known as bio-inspiration. Because bat wings are so adept at navigating confined areas, they were selected as the study's inspiration. There was a void in the development of MAV wings that closely resembled bat wings, and earlier research in this field frequently employed conventional wing shapes.

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FSI CFD simulation with ANSYS V1.6 software and experimental validation in a subsonic wind tunnel comprised the study methodology. A 2-way Fluid-Structure Interaction (FSI) approach was used in the simulation to create the wing geometry, which was based on an observation of a bat wing. The wing model was 3D printed as part of the experimental study, and lift generation was measured with strain gauges and a data-gathering system.

The study found that the wing design, based on the structure of bat wings, was able to generate significant lift with a stall angle of 25⁰. The simulation model demonstrated a close agreement with the experimental results, indicating its validity for future wing design and flight conditions. The study's findings provide a foundation for the future design of a flying flapping wing MAV inspired by natural bat wings.

C. Design and Research on Flapping Mechanism of Biomimetic Albatross by Haiming Zhang (zhmdyx7@163.com) [Tianjin Key Laboratory for Advanced Mechatronics System Design and Intelligent Control, School of Mechanical Engineering, Tianjin University of Technology, Tianjin, 300384, China]; Zhenzhong Liu (zliu@email.tjut.edu.com) [National Demonstration Centre for Experimental Mechanical and Electrical Engineering Education, Tianjin University of Technology]

The creation of a high-efficiency flapping wing structure motivated by albatross flying characteristics is the subject of this research study. The low flying efficiency and subpar aerodynamic performance of flapping wing aircraft are often discussed in this study. The paper addresses the design method for bionic structures and derives design requirements for a bionic wing structure through an examination of albatross flying characteristics. This entails figuring out, analyzing, and optimizing important variables like the connecting rod mechanism's size and angle. Furthermore, a three-dimensional SolidWorks model of the flapping wing mechanism is built for motion analysis, and a clamping mechanism is devised to achieve gliding kinetic energy.

In addition to highlighting the suitability of flapping wing motion at low Reynolds numbers and small wingspans, the research underlines the significance of flapping wing flight for flying organisms. It summarizes earlier research on the topic and talks about the current state of research on bionic flapping wing aircraft, highlighting the significance of theoretical investigation and structural design. In particular, the restrictions of weight, size, and mechanical structure rigidity that cause flapping wing aircraft to perform poorly aerodynamically and have limited flight times and distances are the main topics of this work.

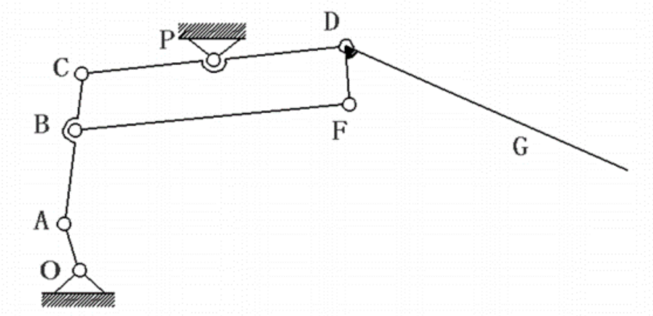

Fig. 10 Schematic Diagram of Albatross Flapping Mechanism

Additionally, the paper summarizes the flutter and glide flight characteristics of albatross wings by a thorough analysis of their structural properties. The structural design of a biomimetic flapping wing resembling an albatross is then described in detail, including the flapping mechanism design specifications, the bionic design goals, and the degrees of freedom calculation for the system. Also given are the design and parameter optimization for the flapping wing size.

Using SolidWorks for three-dimensional modeling and motion analysis, the paper finishes with the modeling and simulation analysis of the flapping wing mechanism. The simulation results show that the suggested flapping wing mechanism is effective and validates the design goals.

In conclusion, the research provides a thorough examination of the creation of a high-efficiency flapping wing construction that draws inspiration from albatross flight mechanics. It offers insightful information on motion simulation, structural analysis, and bionic design to enhance the performance of flapping wing aircraft.

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D. Dynamic Analysis of the Flapping Mechanism of Flapping Wing Aircraft by Wei He, Ruikun Zhang, Lei Sun, Xu Chen, and Xiao Luo [School of Mechatronic Engineering, Southwest Petroleum University, Chengdu 610500, China]

The study report provides a thorough examination of the crank and rocker mechanism flapping mechanism of a flapping-wing aircraft. The purpose of the study is to comprehend how the air-undulating moment acts on the motor and how the load-undulating moment affects it. The flapping mechanism's kinematics model is established at the outset of the study, and then the Lagrange dynamic equation is used to derive the dynamic model. The torque fluctuation on the crank during the flapping flight is then computed using MATLAB, and the aerodynamic moment of the flapping aircraft is then determined using the strip technique. The system is simulated using ADAMS software to confirm the accuracy of the model, and the simulation results are in agreement with the model's computed results, demonstrating the correctness of the model.

The study addresses the benefits of flapping wings over fixed-wing and rotor-wing aircraft and emphasizes the significance of the Micro-Fly-Winged Aircraft (FMAV) as a novel concept aircraft. To meet the requirements for the bionic function, the study highlights the necessity of developing the flight realization scheme and examining the kinematics and dynamics of the flapping wing aircraft. Kinematics and dynamics studies of the crank rocker mechanism are conducted, and it is described as the most suited mechanism for downsizing.

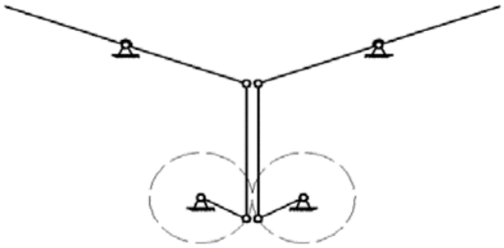

Fig. 11 Sketch of the Flapping Wing Mechanism

The research report also offers thorough explanations of the flapping mechanism's kinematic and dynamic analyses. It goes over how the flutter mechanism model was created, how the flapping mechanism's location was examined, and how the fluttering mechanism's acceleration was examined. To examine the motion parameters and mechanism performance, mathematical formulae and geometric correlations are used. To validate the model, MATLAB is used to calculate and simulate the flutter mechanism's length size, angular displacement, velocity, and acceleration.

To confirm the model's accuracy, the study also runs ADAMS motion and dynamics simulations. The simulation findings confirm the accuracy of the kinematics analysis by showing agreement with the theoretical calculation results. The paper also discusses the flapping-wing aircraft model's dynamic simulation analysis, with an emphasis on the aerodynamic forces, the crankshaft's balance moment, and the impact of variable torque on the motor. The outcomes validate the accuracy of the dynamic model by showing concordance between the theoretical computation and simulation results.

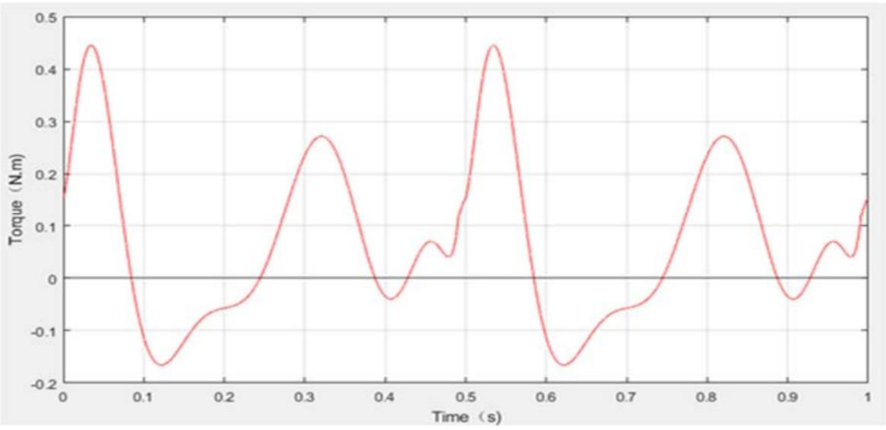

Fig. 12 ADAMS Simulation Crank Balance Torque Curve

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The study concludes by highlighting how crucial it is to create and evaluate mathematical and dynamic models to comprehend the behavior of flapping-wing aircraft that include a crank and rocker system. The results offer a solid basis for the development and examination of comparable propulsion systems, advancing the domain of flapping-wing aircraft technology.

E. Mechanism Design and Aerodynamic Research of Retractable Folding Flapping Wing by Yuanbo Li, Wenqing Yang, Ang Chen & Rui Zhang [School of Aeronautics, Northwestern Polytechnical University, Xi'an 710072, China]

The main goal of the study is to develop and numerically examine a folding wing mechanism that draws inspiration from the structure of bat wings. The study entails the kinematics analysis using the CATIA motion simulation module, the design of a locking and driving mechanism, and the extraction and simulation of bat wing skeletal components. Computational Fluid Dynamics (CFD) simulation is utilized to investigate the impact of wingspan contraction on lift and thrust. The simulation elucidates the effects of spanwise contraction on lift and thrust.

The research on flapping wing aircraft and the relatively unexplored design of bat-like aircraft is covered in the first section of the paper. The presentation includes a range of mechanical wing prototypes created by several researchers to replicate the physiological makeup and retractable nature of bat wings. The examination of the physiological makeup and retractable properties of bat wings is then covered in detail, along with the skeletal composition and the dynamics of spanwise folding during flight.

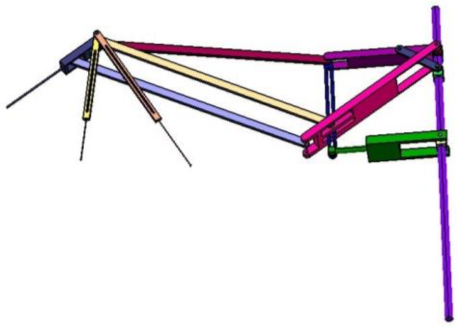

Fig. 13 3D Model of Bat-Like Folding Mechanism

Next, a detailed description of the retractable folding wing mechanism, resembling a bat, is given. A detailed explanation is provided for the 2D design of the folding mechanism, which includes the inner, middle, and outer wing portions, as well as the main and auxiliary connecting rods. The construction of a locking mechanism and a single-degree-of-freedom gear drive system to accomplish the coupling of flapping and folding actions is also covered in this work.

The study also includes numerical simulations utilizing Computational Fluid Dynamics (CFD) to evaluate the aerodynamic performance of the folding wing mechanism. The simulations, which compare a rigid wing to a retractable wing, show that the wingspan contraction during the upstroke increases average lift while concurrently decreasing thrust and decreasing negative lift.

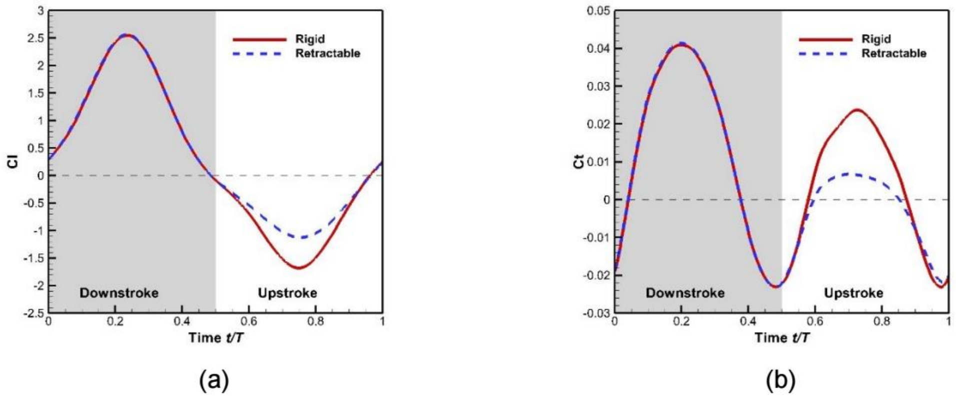

Fig. 14 Curves of Lift Coefficient and Thrust Coefficient of Retractable Wing and Rigid Wing.

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The study concludes with a thorough analysis of the aerodynamic performance and design of a retractable folding wing mechanism modeled after a bat's wing. The work provides insightful information about how bat-inspired systems might improve the aerodynamic performance of aircraft with flapping wings. The Chinese National Natural Science Foundation and the Shaanxi Province's Key R&D Program provided funding for the project.

III. CONCLUSION

Finally, a thorough review of the literature on foldable flapping wing mechanics in biomimetic robots has shown a plethora of new ideas, innovative approaches, and possible uses. It is clear from the compilation of numerous research that these mechanisms have a lot of potential for creating flexible and effective robotic systems that resemble birds in flight. Even though we now have a solid understanding of the design concepts, manufacturing processes, and control schemes related to foldable flapping wing devices, there are still several issues that need to be resolved. To achieve more lifelike flight, these difficulties include improving robustness, scalability, and maneuverability as well as deepening our grasp of biomechanics and aerodynamics. Notwithstanding these difficulties, the multidisciplinary character of this field's research fosters creativity and generates fresh ideas for solutions.

Looking ahead, interdisciplinary collaboration, breaking down barriers between theory and practice, and investigating new ways to get beyond current constraints should be the main goals of future research projects. Foldable flapping wing systems have the potential to transform the field of biomimetic robotics and open the door for the construction of cutting-edge aerial vehicles with previously unheard-of capabilities by tackling these issues and building on the groundwork established by earlier research.

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