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# A Review of Flapping Mechanisms for Avian-Inspired Flapping-Wing Air Vehicles

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**Abstract:** This study focuses on the flapping mechanisms found in recently developed biometric flapping-wing air vehicles (FWAVs). FWAVs mimic the flight characteristics of flying animals, providing advantages such as maneuverability, inconspicuousness, and excellent flight efficiency in the low Reynolds number region. The flapping mechanism is a critical part of determining the aerodynamic performance of an FWAV since it is directly related to the wing motion. In this study, the flight characteristics of birds and bats are introduced, the incorporation of these flight characteristics into the development of FWAVs is elucidated, and the utilization of these flight characteristics in the development of FWAVs is explained. Next, the classification and analysis of flapping mechanisms are conducted based on wing motion and the strategy for improving aerodynamic performance. Lastly, the current research gap is elucidated, and potential future directions for further research are proposed. This review can serve as a guide during the early development stage of FWAVs.

**Keywords:** flapping-wing air vehicle; flapping mechanism; avian-inspired aircraft; robotics

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## 1. Introduction

Flying animals such as birds and insects can fly effectively in complex and diverse environments. They have high flight efficiency, maneuverability, and environmental adaptability—characteristics that are difficult for human-made aircraft to replicate [1–3]. Various studies have been conducted to develop flapping-wing air vehicles (FWAVs) that mimic the excellent flight characteristics of these flying animals. Flying animals fly at a relatively lower Reynolds number than existing manned aerial vehicles, as shown in Figure 1 [4]. The Reynolds number is a dimensionless quantity that represents the ratio of inertial forces to viscous forces of a fluid. The reduced frequency is a dimensionless number representing the ratio of forward speed and flapping frequency. However, unmanned aerial vehicles (UAVs) operating in the low Reynolds number region can be improved by applying these advantageous animal flight characteristics.

Recently, with the increased use of UAVs, studies on biomimetic FWAVs have increased. Unlike rotorcraft, FWAVs do not use blades to obtain propulsion, providing relatively low noise and increased collision safety. In addition, they can be used for military purposes such as reconnaissance and surveillance because of their inconspicuous flying animal-like appearance. Festo's Smartbird [5] was designed by imitating the flight of a seagull, and AeroVironment's Nano hummingbird [6] was developed to have an appearance and flight characteristics similar to a hummingbird—flying forward and backward as well as hovering similar to a hummingbird. This model can perform real-world reconnaissance missions as it can obtain image information through a micro-camera.

Flying animals can be classified into insect or avian-scale [7]. Insects fly using a single-articulated wings connected to a thoracic hinge. Aerodynamic force is obtained through passive deformation of the wing shape [8]. Conversely, birds and bats have multi-articulated wings to increase aerodynamics through active wing deformation [9].

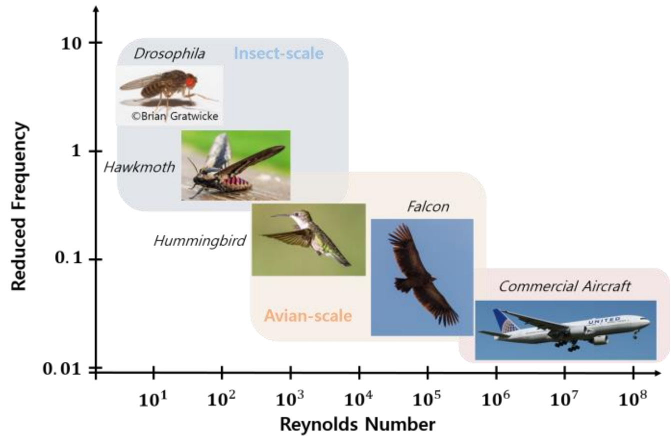


**Figure 1.** Aerodynamic characteristics of flying animals, Reynolds number vs. reduced frequency (adapted from [4]; photograph from Brian Gratwicke and open-source photographs).

FWAVs can also be classified as avian or insect-inspired according to the flapping frequency and wing size. Insect-inspired FWAVs are driven at a high flapping frequency and can be used for indoor surveillance and reconnaissance. However, they are not suitable for performing outdoor missions due to their low stability against disturbance, relatively short flight time, and low payload capacity. However, avian-inspired FWAVs are driven at a relatively low flapping frequency, enable increased endurance by gliding, and are robust when performing outdoor missions because of their large payload capacity. In this paper, the standard for avian-inspired FWAV is an aircraft with a wingbeat frequency of less than 30 Hz, a wingspan of 200 mm or more, and mainly for forward flight rather than hovering.

Currently, most FWAVs are insect-inspired (from 1984 to 2014 [10]). Avian-inspired FWAVs are still in the development stage, and not many have been actively used in comparison to insect-inspired FWAVs. Recently, studies to improve avian-inspired FWAV performance have been actively conducted, and they are expected to overcome the stability and payload capacity limitations of insect-inspired FWAVs. Unlike insect-inspired FWAVs, which focus on light weight and high flapping frequency, avian-inspired FWAVs focus on withstanding relatively large loads due to their large wingspan. An FWAV flapping mechanism consists of an actuator and a transmission mechanism and converts the rotational or linear motion of the actuator to generate wing motions and, subsequently, aerodynamic force. Since the flapping mechanism generates aerodynamic force, it is a critical part in determining aerodynamic performance. In addition, the concept and development process of the flapping mechanism must differ based on the FWAV operating purpose and environment. Therefore, a review of the flapping mechanisms for avian-inspired FWAVs can be a valuable guide in the early FWAV development stages.

In this paper, the mechanisms for avian-inspired FWAVs are reviewed. The avian flight characteristics are first introduced, followed by an explanation of how current studies have successfully mimicked these flight characteristics. Next, various flapping mechanisms are classified and analyzed according to wing motion and the strategy for improving aerodynamic performance. Finally, the current research gap in FWAV studies is explained, and future directions for research in this field are proposed.

## 2. Avian Flight Characteristics

Flying animals are products of evolution with optimal flight performance according to their habitat, and their excellent aerodynamic flight characteristics provide great inspiration to engineers. By discussing which wing motions effectively generate aerodynamic force and which flight strategies they adopt, applicable strategies for FWAVs can be understood.

It is known that flying animals in nature can effectively fly in various and complex flight environments using their flapping wings [1,11,12]. Aerodynamic performance and efficiency can be improved by appropriately combining various wing motions. Various wing motions can be generated due to musculoskeletal interactions, as shown in Figure 2 [13–15].

During the flapping flight, most flying animals fold their wings during the upstroke by flexing the elbow and adducting the wrist, as shown in Figure 2a (wing folding) [16]. By folding the wing, drag and inertial cost are reduced because the wing's moment of inertia can be reduced while reducing the span [17].

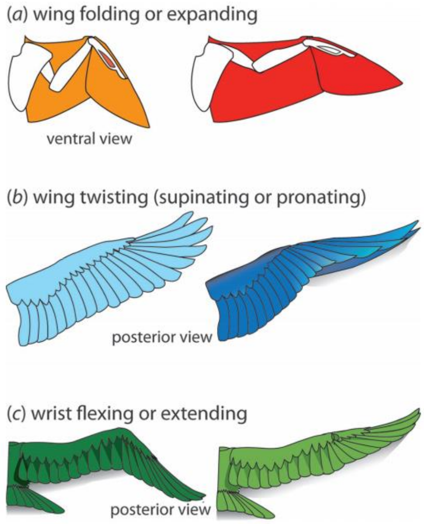


**Figure 2.** Wing motions of flying animals (**a**) wing folding, (**b**) wing twisting, and (**c**) wrist flexing. Reprinted with permission from Ref. [14]. 2015, Canadian Science Publishing.

The twisting motion of the wing indicates that it rotates in the longitudinal direction of the wing, as shown in Figure 2b (twisting). Wings can be passively twisted by structural deformation and actively twisted through pronating and supinating the wrist [1,18]. By twisting the wing, wing tip stall can be prevented because the angle of attack is reduced at the wing tip. In addition, the flight speed can be controlled, or thrust can be increased by adjusting the twisting angle [19–21].

Flying animals can bend their wings perpendicular to the plane of the wing, as shown in Figure 2c (wrist flexing). In general, their wings are bent during the upstroke and extended during the downstroke—similar to folding and expanding. By flexing the wrist, they can achieve similar benefits to wing folding. As the wing bends during the upstroke, the moment of inertia of the wing is reduced, resulting in efficient flight. Wing folding and wrist flexing often occur simultaneously, resulting in increased lift and reduced drag compared to without wing bending and wrist flexing [22].

Muscles drive the flapping motion of birds and bats [23,24]. A bird's wings are composed of overlapping feathers, whereas a bat's consists of membranes. Birds usually bend their wings, and bats mainly fold their wings during the upstroke to increase aerodynamic efficiency [25]. Most birds can achieve cruising flight at all flight speeds, while hummingbirds and bats can perform low-speed maneuvering [26].

Flying animals adopt different flight strategies according to the flight environment and change their wing motions according to the flight speed [11,27,28]. In low-speed flight, birds with a high aspect ratio twist their wing until the wing tips are inverted with a large twisting angle. Hummingbirds fold less in hovering flight mode [29], and the folding angle varies depending on flight speed [30]. In addition, pigeons decrease their wing span, wing area, and aspect ratio by folding their elbow as their flight speed increases [31].

Flying animals increase their flight performance through various flight strategies and wing movement changes. Intermittent flapping is one such strategy which increases flight efficiency. For example, flapping-bounding is when wings are fixed to the body during flight, and flapping-gliding is when the wing is extended during flight.

Flapping-bounding mainly occurs in small-sized birds [32] and preserves energy in high-speed flight [33]. Rather than extending the wings to generate lift, they fold their wings to reduce drag and create lift from the body and tail wing. In flapping-gliding, the wing is extended to avoid continuous flapping at all flight speeds, thereby saving energy [32].

Bats also adopt a strategy to obtain aerodynamic benefits by reducing the area and span of their wings in high-speed flight [34,35]. However, compared to birds, their change in wing area is limited. For birds, it is easy to reduce the area of the wing because the feathers are separately overlapped; however, bat wings consist of membranes [36]. For example, pigeons can reduce their wing span and area to 37% and 62% of their maximum value [37], while dog-faced bats can only reduce their wing span and area to 83% and 70% of their maximum value [36]. Instead, bats can adjust the camber of their wings according to flight speed, so they can more effectively generate high lift at high angles of attack [9].

## 3. Flapping Mechanism

The following section provides an analysis of how flapping mechanisms emulate the wing motions of flying animals, and the aerodynamic advantages derived from the flapping motions are discussed.

### *3.1. Classification of the Flapping Mechanism According to Wing Motions*

The wing motions of currently developed FWAVs are different from those of actual flying animals. This is because, unlike animal wings that are composed of muscles and bones, FWAVs are composed of actuators and transmission mechanisms, making it difficult to realize all the complex wing motions found in avians. Due to these limitations, FWAVs have used mechanisms that realize only some wing motions rather than imitating all the wing motions of flying animals.

Depending on the wing motion, flapping mechanisms can be classified into those that can generate motion in one axis or those that can generate multi-axis, as shown in Figure 3.

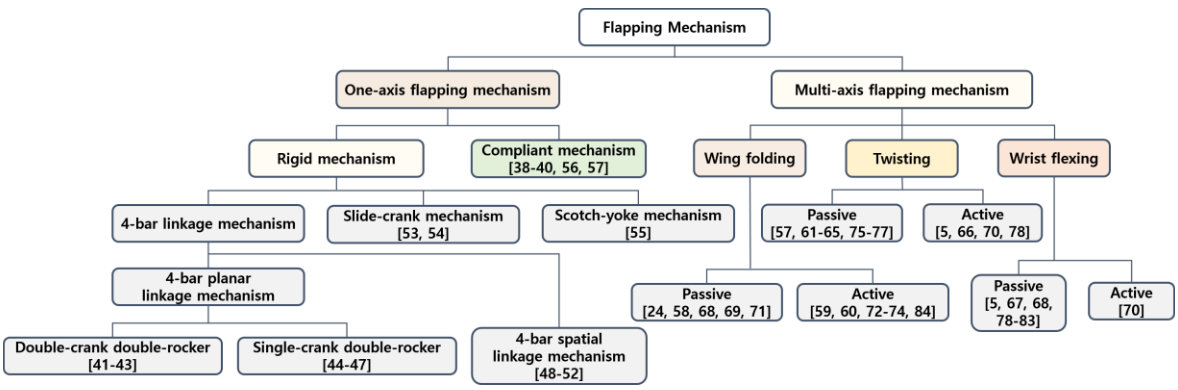


**Figure 3.** Classification of flapping mechanism: one-axis flapping mechanism vs. multi-axis flapping mechanism [5,24,38–84].

#### 3.1.1. One-Axis Flapping Mechanism

Mechanisms that can only move in one axis have the advantage of reducing weight and complexity due to utilizing a simple mechanism. One-axis flapping mechanisms can be classified into rigid mechanisms and compliant mechanisms. A rigid mechanism refers to a mechanism in which all parts of the mechanism are rigid parts, and a compliant mechanism refers to a mechanism including at least one flexible part, such as some compliant joints.

Rigid mechanisms

A four-bar linkage mechanism is a typical mechanism capable of one-axis motion. These include a four-bar planar linkage mechanism based on the crank-rocker mechanism using four revolute joints and a four-bar spatial linkage mechanism using two spherical joints and two revolute joints, as shown in Figure 4a–c.

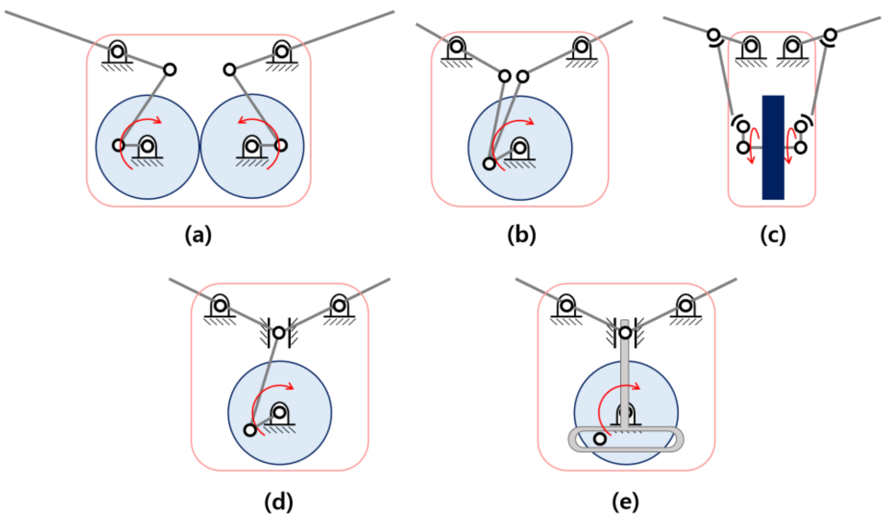


**Figure 4.** Rigid mechanism (**a**) four-bar planar linkage mechanism (double-crank double rocker mechanism) (**b**) four-bar planar linkage mechanism (single-crank double rocker mechanism) (**c**) four-bar spatial linkage mechanism (**d**) slide-crank mechanism (**e**) scotch-yoke mechanism.

There are also double-crank double-rocker mechanisms (Figure 4a) and single-crank double-rocker mechanisms (Figure 4b) based on the four-bar planar linkage mechanism. The single-crank double-rocker mechanism has a relatively small body width because it can drive two couplers and rockers by one crank; however, a phase difference between both wings occurs, causing asymmetric wing motion. Wang et al. [85] addressed this issue by defining the phase difference of both wings as the optimization problem. Meanwhile, the double-crank double-rocker mechanism can drive each rocker with each crank, and the two cranks are driven simultaneously with a pair of gears without phase difference between both wings. For this reason, the double-crank double-rocker mechanism has been used in many FWAVs.

A four-bar spatial linkage mechanism operates in 3D space, as shown in Figure 4c, and the direction of the flapping motion and the rotation direction of the crank are perpendicular. This mechanism can greatly reduce the width of the body, consequently reducing the drag generated by the body. Since the four-bar linkage mechanism is easily combined with a DC motor, can be driven with relatively low voltage, and has high energy efficiency and maximum torque, it has been widely used, from avian-inspired FWAVs with large wings to insect-inspired FWAVs with small wings. However, the flapping angle amplitude that can be implemented with a four-bar linkage mechanism is not large.

Additionally, there are cases in which flapping motion has been generated using a slide-crank or scotch-yoke mechanism, as depicted in Figure 4d,e, respectively. A slide-crank mechanism converts the rotational motion of the motor into linear motion. Using linear motion, it can then overcome the limited flapping angle amplitude of the four-bar linkage mechanism or implement various wing motions. Similar to the slide-crank mechanism, a scotch-yoke mechanism uses rotational motion of the actuator to generate linear motion as the slider and the piston connected to the slider reciprocates. Unlike the slide-crank mechanism, it generates a simple harmonic motion.

Compliant mechanisms

Unlike the rigid mechanism composed of rigid links and joints, a compliant mechanism is composed of flexible materials that can be deformed. Compliant mechanisms have mainly been used for insect-inspired FWAV because they have less friction, can be manufactured in a small size, and are light compared to flapping mechanisms composed of rigid bodies. Compliant mechanisms are classified into flexible frames and flexible joints.

Madangopal et al. [38] proposed a design concept of the flapping mechanism that combines springs with joints of a four-bar linkage mechanism. The kinetic energy of the wing is stored in the form of elastic energy and then released again as kinetic energy.

Figure 5a illustrates a mechanism that produces the same effect by combining a linear spring with the slide of the slide-crank mechanism.

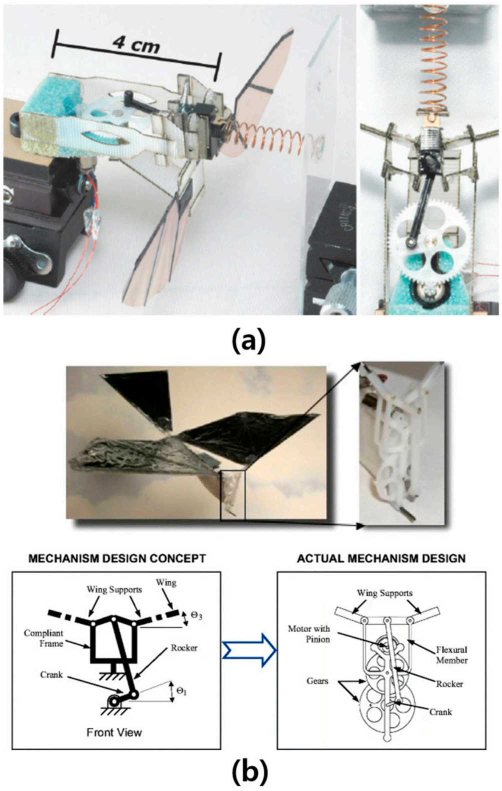


**Figure 5.** Compliant mechanism (**a**) flexible joint. Reprinted with permission from Ref. [39]. 2009, IEEE. (**b**) flexible frame. Reprinted with permission from Ref. [40]. 2009, Springer Nature.

To solve the mechanical vibration and abrasion problem of the rigid mechanism, the compliant frame flapping motion can be driven by flexible frame instead of rigid linkages. The mechanism effectively reduced the mass of the operating part. The compliant mechanism can also reduce the difference between largest and smallest load, thus improving the reliability of the electronic components. Figure 5b shows one example of the flexible frame flapping mechanism [40]. The frame of this mechanism was manufactured as single piece by using injection molding. However, since it is inferior to the rigid mechanism in terms of transmission efficiency, it is less suitable for avian-inspired FWAVs with relatively large and heavy wings compared to insect-inspired FWAVs. For these reasons, compliant mechanisms have been used as an additional mechanism to generate other wing motions rather than being used in the driving mechanism to generate flapping motion.

The classification and reference of one-axis flapping mechanisms are listed in Table 1.

**Table 1.** Classification of one-axis flapping mechanism.

| Type | Mechanism | Refs. |
|---|---|---|
| **Rigid mechanism** | Four-bar planar linkage mechanism double-crank double-rocker | [41–43] |
| | Four-bar planar linkage mechanism single-crank double-rocker | [44–47] |
| | Four-bar spatial linkage mechanism | [48–52] |
| | Slide-crank mechanism | [53,54] |
| | Scotch-yoke mechanism | [55] |
| **Compliant mechanism** | Flexible joint | [38,39,56,57] |
| | Flexible frame | [40] |

### 3.1.2. Multi-Axis Flapping Mechanism

The flapping mechanisms introduced above can only generate flapping motion and require an additional mechanism or actuator to increase stability, maneuverability, and aerodynamic performance. To improve aerodynamic performance, mechanisms that can generate multi-axis have been studied, and several benefits have been obtained by imitating the wing motion of flying animals.

Wing folding and flapping mechanisms

Folding motion is mainly seen in FWAVs that mimic bats. Many foldable FWAVs have used an articulated mechanism that utilizes wing linkage to implement folding motion. The folding mechanism is similar to the skeleton structure of flying animals, and the wings can be folded through the mechanism, as shown in Figure 6. The mechanism has a prismatic joint with a linear motion driven by a slide-crank mechanism or a servo motor.

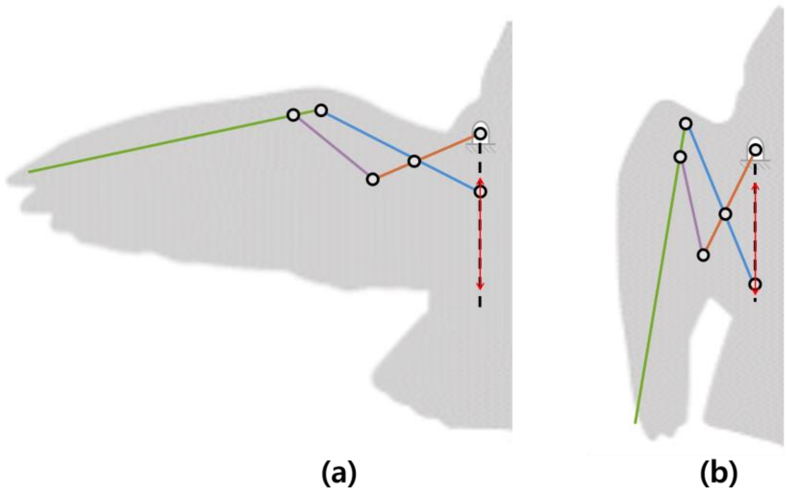


**Figure 6.** Wing folding linkage mechanism (**a**) during downstroke (**b**) during upstroke.

Hoff et al. [58] developed a flapping mechanism similar to the skeleton of a bat's wing using rigid links and joints. The flapping mechanism is a one-degree-of-freedom mechanism that can simultaneously generate flapping motion and folding motion. Chen et al. [59] developed a folding mechanism composed of links and joints, which can be folded similarly to the structure of a bird's wing; servo motors control whether each wing is folded or not folded. Roll control is performed by the folding motion of each wing, and the mechanism has three degrees of freedom. As mentioned earlier, due to their lightness and low friction, research on implementing folding using compliant mechanisms has also been conducted [60].

Stowers et al. [24] developed a passive folding mechanism that has a pin joint in the center of the leading edge of the wing without linkages. The mechanism uses centrifugal accelerations induced by the flapping motion to fold the wing. This mechanism can quickly unfold its wings and is lighter and more energy-efficient.

As mentioned earlier, when using rigid mechanism, it is easy to implement the desired wing-tip trajectory. However, when using compliant mechanism, it is difficult to create the desired trajectory. It is implemented passively, so there is a disadvantage in the fact that the trajectory changes depending on the operating environment.

Twisting and flapping mechanisms

Twisting mechanisms are divided into the non-structural twisting mechanism (Figure 7a) and the structural twisting mechanism (Figure 7b). The non-structural twisting mechanism is mainly used to implement a figure-of-eight wing tip trajectory of flying animals. The twisting motion can be implemented by combining more than two mechanisms, such as a six-bar linkage mechanism [63], a double scotch-yoke mechanism [64], a combination of a crank-rocker and eccentric sphere mechanism [65], etc.

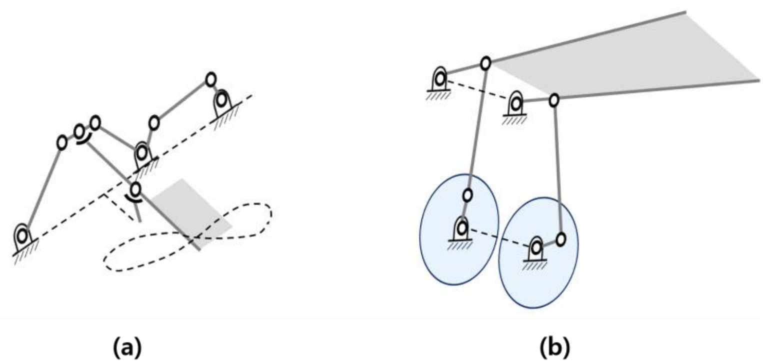


**Figure 7.** Twisting linkage mechanism (**a**) twisting motion mechanism (adapted from [61]) (**b**) structural twisting mechanism (adapted from [62]).

On the other hand, the structural twisting mechanism uses the structural flexibility of the wing. Hu et al. [62] developed a mechanism to structurally twist the wing by placing two crank-rockers parallel to the wing leading edge spar and sub spar, respectively, with phase differences. Kim et al. [66] and Send et al. [5] developed mechanisms that change the structure of the wing by installing an additional actuator on the wing. Kim et al. [66] developed a smart wing with a macro fiber composite actuator to morph the wing structure according to an input voltage. In addition, in the study of Send et al. [5], the wing structure was morphed by using a servo motor at the wing tip.

When performing torsional motion through a mechanism, there is the disadvantage of increased complexity and weight of the driving unit. On the other hand, when creating structural torsion of the wing itself, there is the disadvantage of increased complexity and weight of the wing structure. Therefore, for small-span flight vehicles with high-frequency operation, it is advantageous to implement torsional motion through a mechanism due to the additional torque required by the increased wing weight when using a wing mechanism that facilitates the structural torsion of the wing.

Wrist flexing and flapping mechanisms

A representative mechanism for implementing flexing is the flapping mechanism of Festo's Smartbird. This mechanism consists of links and joints, as shown in Figure 8. It is divided into a crank-rocker mechanism constituting the movement of the inner wing and an outer wing mechanism, and has one degree of freedom. Meanwhile, a study has been conducted to passively bend the wing using a compliant spine, and has a lighter and simpler wing structure compared to the rigid mechanism [67].

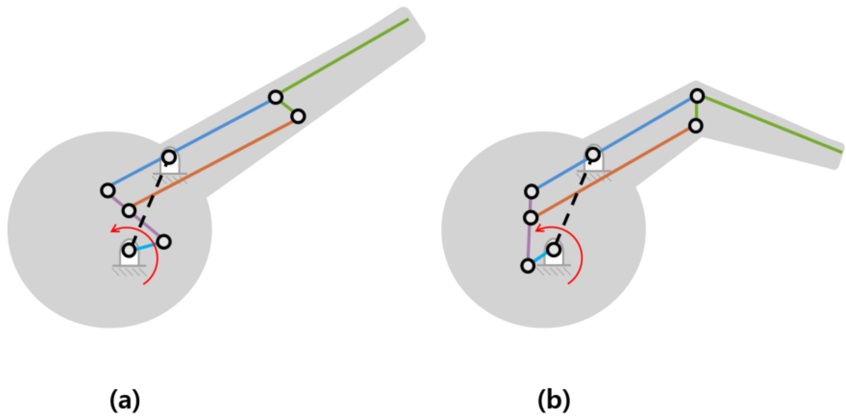


**Figure 8.** Wrist flexing linkage mechanism (**a**) during downstroke (**b**) during upstroke.

Dewangan et al. [86] proposed a new concept of flexing mechanism using rigid linkages. Although it is still in the concept stage, it has the advantage of being able to increase lift while quickly folding using a crank slotted lever mechanism.

Similar to the aforementioned folding mechanism, the rigid mechanism enables easy implementation of the intended trajectory, but the compliant mechanism has the disadvantage of being difficult to implement the intended trajectory and may not be able to implement wrist flexing motion depending on the flight speed or operating environment. Both wrist flexing and folding mechanisms have the disadvantage of making the wing structure more complex and heavier. In particular, the rigid linkage mechanism requires additional links and joints compared to the mechanism that only performs the one-axis wing motion. The rigid linkage mechanism is suitable for FWAVs with a large span that can generate a large lift force to compensate for the increased weight, while for small FWAVs, the compliant mechanism is relatively lightweight and simple, making it suitable.

Other flapping mechanisms

Like flying animals that increase aerodynamic efficiency by realizing several wing motions simultaneously, studies have been conducted to simultaneously generate three or more wing motions. Adding links and joints or actuators to generate complex motions increases the weight and complexity. Many researchers have developed ways to simply create additional motion. Hoff et al. [68] added a spring hinge to the wing joint of a bat-inspired FWAV in which flapping, wing folding, and wrist flexing occur simultaneously.

Jitsukawa et al. [69] implemented a mechanism capable of feather spreading and wing folding. The flapping mechanism requires a total of two actuators: one for the spreading and folding motion and the other for the flapping motion. Although the mechanism generated enough thrust, it was not found that it can generate enough lift force.

Meanwhile, in [70], a mechanism was developed that can actively implement and control flapping, flexing, and twisting by using servo motors. This FWAV is to be used in wind tunnel tests to analyze aerodynamic characteristics according to various parameters.

The classification of FWAVs that use a multi-axis flapping mechanism is summarized in Table 2.

**Table 2.** Classification of multi-axis flapping mechanism.

| Motion | Type | Mechanism | Refs. |
|---|---|---|---|
| **Wing folding** | Passive * | Rigid mechanism | [24,58,68,69] |
| | | Compliant mechanism | [71] |
| | Active ** | Rigid mechanism | [59,84] |
| | | Compliant mechanism | [60,72–74] |
| **Twisting** | Passive | Rigid mechanism | [61–65,75,76] |
| | | Compliant mechanism | [57,77] |
| | Active | Rigid mechanism | [5,70,78] |
| | | Compliant mechanism | [66] |
| **Wrist flexing** | Passive | Rigid mechanism | [5,78–83] |
| | | Compliant mechanism | [67,68] |
| | Active | Rigid mechanism | [70] |
| | | Compliant mechanism | - |

* passive: Different motions occur simultaneously while flapping without increasing the degree of freedom.
** active: As the degree of freedom increases, an additional actuator is required, and individual control is possible.

### *3.2. Classification of the Flapping Mechanism According to Strategy for Aerodynamic Performance Improvement*

As mentioned above, flying animals combine a flapping motion with other motions to improve aerodynamic performance. Studies have been conducted to imitate these flight strategies and apply them to FWAVs. Some FWAVs add different motions to existing mechanisms, either passively or actively. Aerodynamic performance can be categorized into three types: thrust increase, lift/drag ratio increase, and flight efficiency increase. Most FWAVs focus on specific aerodynamic performance improvement according to flight environment and purpose, and these strategies are discussed below. This section can be a reference for selecting a flapping mechanism according to operational purposes.

#### 3.2.1. Strategies for Increasing Thrust

FWAVs have been studied with the expectation that they can perform various missions by replacing existing fixed-wing UAVs. However, the performance and efficiency of FWAVs are currently inferior to those of actual flying animals or fixed-wing UAVs. Unlike fixed-wing UAVs, which have separate devices for generating thrust, FWAVs struggle to generate sufficient thrust because only one pair of wings generate both lift and thrust. Efficient generation of thrust is an important challenge in the development of FWAVs.

An effective way to generate thrust is to use twisting, as mentioned above. The twisting motion of a wing can be obtained by the multi-axis flapping mechanisms highlighted above. A one-axis flapping mechanism can also generate twisting motion by wing deformation from aerodynamic and inertial force. Therefore, even a simple mechanism can be used to generate thrust. Xue et al. [87] conducted a study to increase thrust by using wing deformation. To vary the deformation of the wing, the natural frequency was changed, and a static thrust measurement test was performed according to the different natural frequencies of the wing.

Research on increasing thrust using flapping mechanisms has also been undertaken. The flapping mechanism of Jiang et al. [65] combines a crank-rocker mechanism and an eccentric sphere mechanism, which can generate a figure-of-eight wing motion. Using this mechanism, thrust was increased by 64.3% compared to a one-axis mechanism that can only generate flapping motion.

#### 3.2.2. Strategies for Increasing Lift/Drag Ratio

Wing folding or wrist flexing is used to increase the lift/drag ratio of FWAVs. During the downstroke, more lift can be generated by increasing the wing area, and during the upstroke, negative lift and drag can be reduced by decreasing the wing area.

Ryu et al. [88] developed a wrist flexing–flapping mechanism and searched the parameters to maximize the flapping amplitude. It was confirmed that lift increased compared to the proposed mechanism with a one-axis flapping mechanism. The flapping mechanism outlined by Wissa et al. (flapping–flexing mechanism) reduced energy consumption and increased lift through the compliant spine at the center of the wing [67]. In addition, Hoff et al. [58] achieved 89% increased lift compared to non-folding mechanisms by using their bat-inspired folding-flapping mechanism. Li et al. [84] proposed a bat-type flapping–folding mechanism. The flapping motion is implemented based on the rigid linkage mechanism, and the locking system fully spreads the wings during the downstroke, and controls the folding by retracting and expanding the wings during the upstroke. There is no prototype of the mechanism, but aerodynamic analysis has demonstrated an increase in average lift.

In addition, the wings of Festo's BionicSwift [89] are separated in a similar manner to bird feathers to increase the lift/drag ratio. During the upstroke, individual feathers separate to allow air to flow and reduce drag. During the downstroke, the feathers stick together to increase lift.

#### 3.2.3. Strategies for Increasing Flight Efficiency

Flying animals adopt a variety of flight strategies to increase flight efficiency. As mentioned earlier, gliding-flapping or bounding-flapping is a strategy for saving energy during flight. However, few FWAV models have implemented these strategies. Some studies have been conducted to develop strategies to reduce energy consumption through gliding flight. For example, Robird can stop flapping and transit to glide mode by using a latching mechanism [75,90]. Zhang et al. [91] proposed a mechanism that can transition to glide mode by adding a gear-locking mechanism to the mechanism that enables wrist flexing.

For small-sized birds, wings are intermittently attached to their body to reduce wing drag, thereby reducing energy consumption and performing efficient flight (flapping-bounding). However, it is difficult to find examples of this method being applied to FWAVs, mostly due to increased weight and complexity when the mechanism for flapping-bounding is applied to small avian-inspired FWAVs.

Some studies have been conducted that imitate flight strategies that reduce energy consumption by storing and releasing kinetic energy in the wing muscles during flapping. For the simulation model of the flapping mechanism using a linear spring (introduced in Section 3.1.1) [38], energy consumption was reduced by 30% compared to those without the spring. Hines et al. [56] developed a mechanism for realizing flapping motion by directly connecting springs and wings to each motor. A voltage is applied to the motors, and the flapping motion is implemented directly without going through linkages or mechanisms. The springs directly connected to the motors act as an elastic member and generate flapping motion using resonance. This method hold the advantages of reduced mass and reduced energy consumption.

In addition, research on developing mechanisms to increase stability or maneuverability have been conducted [92,93]. Some examples of flapping mechanisms according to strategies to improve aerodynamic performance are listed in Table 3.

**Table 3.** Flight performance improvement strategy and contribution.

| Objective | Span [mm] | Weight [g] | Wing Motion | Contribution | Validation | Ref. |
|---|---|---|---|---|---|---|
| Thrust | 640 | - | Flapping | Thrust was increased by adjusting the natural frequency of the wing. | Inertial force measurement test | [87] |
| Thrust | 290 | 24.8 | Flapping and twisting | Thrust was increased compared to the mechanism that cannot generate twisting. | Wind tunnel test | [65] |
| Thrust | 940 | 1500 | Flapping, wing folding, and feathered wing | Thrust was increased due to the wing shape changing by the feathers. | Inertial force measurement test | [69] |
| Lift/Drag Ratio | 530 | 79 | Flapping and wing folding | Drag was reduced due to wing folding. | Wind tunnel test | [72] |
| Lift/Drag Ratio | 400 | - | Flapping and wrist flexing | Lift was increased compared to the mechanism that cannot bend. | Inertial force measurement test | [88] |
| Lift/Drag Ratio | 1600 | 1100 | Flapping | Lift was increased by increasing the stiffness of the inner wing. | CFD analysis, wind tunnel test and outdoor flight test | [94] |
| Lift/Drag Ratio | 1500 | 650 | Flapping and wing folding | Lift was increased by searching the parameters of the compliant mechanism with aerodynamic analysis. | Indoor flight test | [71] |
| Lift/Drag Ratio & Flight efficiency | - | - | Flapping and wrist flexing | More lift was generated compared to the case without the complaint spine (45% energy consumption reduction; 16% lift increase). | Inertial force measurement test | [67] |
| Flight efficiency | 2000 | 650 | Flapping and wing folding | By using foldable and flexible wing, it can be driven at a lower flapping frequency and energy consumption can be reduced. | UVLM analysis, indoor and outdoor flight test | [74] |

## 4. Research Topics for Advanced FWAV

Engineers have made great progress and advances in FWAVs, mimicking the superior flight performance of flying animals. However, it is still insufficient to replace existing

UAVs in specific missions. In this section, the issues of the mechanisms used in FWAVs are discussed, and future directions are proposed.

Novel Mechanism Design

As in the previous literature survey, most FWAVs have used simple mechanisms [95]. Additionally, due to the spatial limitations of the flapping mechanism, there are few examples of full implementation regarding the various wing motions of flying animals. Additional motion through a passive or active mechanism will increase aerodynamic performance, and the development of a flapping mechanism that can effectively implement various wing motions of flying animals is still needed in future research.

There are also very limited cases of using strategies that can increase flight efficiency, such as gliding-flapping. Research on the braking mechanism, control system, and transition flight are still required. In addition, most FWAVs do not have mechanisms for take-off and landing. Flying animals can stop flying and rest to save energy. Gomez-Tamm et al. [96] have designed claws driven by a shape-memory alloy allowing an FWAV to take-off. Although there are few cases that have applied this mechanism, efficient flight of FWAVs can be expected through future research.

DC motors have mostly been used to drive the large wings of avian-inspired FWAVs, and the weight of the mechanism is significant. Technologies such as piezo-electric motors play a significant role in reducing the weight of insect-inspired FWAVs. However, due to problems in transmission, torque, and efficiency, there are few cases of piezo-electric actuator application to avian-inspired FWAVs. Therefore, actuator technology itself or actuator selection technology is required.

In addition, it will be possible to increase the performance of the flapping mechanism through the development of manufacturing technology for sophisticated design, the use of lightweight and high-strength composite materials, and the use of 3D printing technology. Carollo et al. [97] used 3D printing technology to prototype a flapping mechanism. The mechanism is characterized by its single-component composition. It has the advantage of being light and easy to manufacture and replace. Although only a concept has been proposed, the technology applied to the mechanism in the paper can be applied to a flapping mechanism mimicking a small bird.

Mechanism design combined with aerodynamic analysis

According to the previous literature, the kinematic design parameters of most flapping mechanisms are selected in a way that imitates flying animals. For the flapping–flexing mechanism (e.g., such as Smartbird [78,79]), kinematic design parameters such as link length, angle, and angular velocity were randomly selected to mimic a real bird without considering the aerodynamic characteristics. The flapping motions of flying animals are clearly efficient (in the low Reynolds number range). However, since there is a large difference in the structural aspects, such as wing size and flexibility, between flying animals and FWAVs, the most efficient flapping motions differ. The optimal wing kinematics are different depending on the flight environment, which involves factors such as wing shape, flight speed, etc. [98,99]. Therefore, it is necessary to effectively predict unsteady aerodynamics according to the flapping motion and search for an efficient flapping motion in the initial FWAV design stage rather than designing a mechanism that simply mimics wing motions.

Recently, research has been conducted to design a flapping mechanism by combining aerodynamic analysis. Kalpathy et al. [100] proposed a model that can obtain lift and energy consumption according to link lengths by combining a kinematic model and the Quasi-Steady aerodynamic model. The link lengths of the mechanism were selected to maximize the lift/power ratio. This method resulted in a 73.8% reduction in energy consumption. It is currently rare to design a flapping mechanism in this way; however, if the flapping mechanism is designed based on the unsteady aerodynamic model that has proven to be reliable, an aerodynamic efficiency increase can be expected.

Mechanism design combining aerodynamic and structural analysis

Due to the limited payload capacity of FWAVs, reducing weight and satisfying the minimum structural requirements of a given flight environment are crucial. Fluid–structure interaction (FSI) analysis is required to confirm whether the structural performance satisfies the given constraints and to optimize structural requirements. In addition, fatigue analysis or an analysis to prove structural robustness is also required to achieve repeatable flight performance. In a flight situation, complex flow occurs, causing structural deformation in the FWAV. Since the wing is deformed by its generated aerodynamic force, thus changing its aerodynamic characteristics, the aerodynamic force changes according to the structure of the wing even with the same flapping mechanism. In addition, it is necessary to consider the effect of the aerodynamic force generated by the wing on the mechanism.

Truong et al. [101] reduced the mass of the gear by 25% while meeting the structural requirements through optimization, but did not consider the aerodynamic effect. There are a few cases in which FSI analysis has been performed on FWAVs. However, if an FWAV is developed based on FSI analysis, it can have increased payload capacity while remaining structurally robust.

Multidisciplinary optimal design of FWAV

Developing FWAVs remains a challenge due to the complexity and lack of well-established means to predict overall design performance. Suitable models must be established and combined to comprehensively predict FWAV performance. Most studies have mainly focused on optimizing only one aspect of flight; however, similar to general aircraft development, FWAVs also use complex systems combining various fields such as aerodynamics, structure, and vibration. Therefore, various technologies must be combined and developed to improve the overall flight performance of FWAVs.

Stanford et al. [102] designed a mechanism through topology optimization that minimizes the mass of the mechanism while maximizing the thrust generated by the complaint flapping mechanism. This process is meaningful in that it uses an integrated finite element model combining aerodynamics, structure, and inertial forces. Khan et al. [57] proposed an optimization technique (shown in Figure 9) that combined aerodynamic, vibration, and dynamic analysis that can satisfy the design requirements and the similar optimization scheme applied in the development of the FWAV prototype named Dove [44].

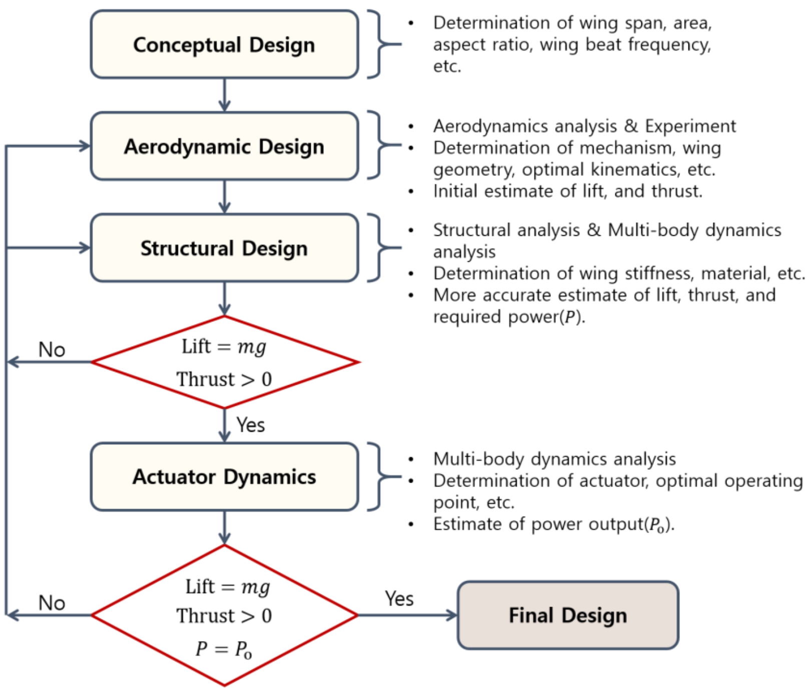


**Figure 9.** Diagram of flapping mechanism design process [44,57].

A well-established design process is required for the successful development of an FWAV, and if designed in consideration of various fields, it can replace existing UAVs and perform various missions.

## 5. Conclusions

Here, a review was conducted on the mechanisms utilized to achieve wing motion in FWAV. Flapping mechanisms were classified and analyzed according to wing motion and aerodynamic performance improvement strategy. The current research gaps found in flapping mechanism development were discussed, and future research directions were suggested. This review will provide guidance in the initial design step of FWAV flapping mechanisms.

FWAVs should be developed in a systematic way considering their overall system. Although the flapping mechanism is an important part of determining kinematics, most have been designed using arbitrary design parameters or by trial-and-error, and there are not many cases designed with aerodynamic analysis. Therefore, it is expected that FWAVs can be actively used in various fields if accompanied by an integrated design process in their initial development stage.

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## Nomenclature

| | |
|---|---|
| FWAV | Flapping-Wing Air Vehicle, |
| UAV | Unmanned Aerial Vehicle |
| CFD | Computational Fluid Dynamics |
| UVLM | Unsteady Vortex Lattice Method |
| FSI | Fluid–Structure Interaction |
| $m$ | Mass |
| $g$ | Gravitational acceleration |
| $P$ | Required power |
| $P_0$ | Estimated power outputs |

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