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EVOLUTION OF FLAPPING WING AERIAL VEHICLES: A REVIEW

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Abstract

The motivation behind the concept of flapping wing aerial vehicles is the flying pattern of several insects and birds. It is very challenging to accurately replicate the design and operation of natural flyers in human-made flapping wing aerial vehicles. Intensive research is being conducted worldwide to address this challenge. After carefully observing the flying patterns of natural fliers, different designs and prototypes of flapping wing aerial vehicles (FWAV) were presented in various studies. Performance and efficiency of FWAV based on different models and techniques were also found to be different. In this study, research activities conducted for the advancement of FWAV have been reviewed. The work done in the context of Micro, Nano, and Pico aerial vehicles have been mentioned and discussed. A lot of research has already been conducted in the field of flapping wing micro aerial vehicles, while the nano and pico aerial vehicles are in the initial stage of development. In the development of flapping wing aerial vehicles, attempts have been made to improve aerodynamic structure, wings design, structural materials, power sources etc. However, there is a need for further work to improve the performance of these miniature human-made fliers.

Keywords: *Flapping wing aerial vehicle, hovering, gliding, unmanned aerial vehicle*.

1. Introduction

The concept of unmanned aerial vehicles (UAVs) was envisaged for the successful execution of some complex operations without endangering the life of a pilot. There has been a lot of progress in the applications and related research of UAVs especially miniature UAVs in the past decades (Petricca et al., 2011). Flapping-wing aerial vehicle is also a type of miniature UAV whose design is inspired by insects and birds. A thorough study and understanding of the unprecedented flight capabilities of insects and birds have been the basis for the development of flapping wing aerial vehicles (FWAVs). They are equipped with great functionalities such as hovering and forward flights. In addition, they are lightweight, small in size, fast-moving and capable in maneuver and disguise (Zhou et al., 2018). Once fully developed, it will be an effective tool for data collections, surveillance, covert operations, military operations, as well as civilian tasks. It was noticed that small sized FWAVs possess improved aerodynamic properties than its counterpart. For a new design of a FWAV, getting enough lift from it is a big challenge. The parameters like flapping frequency, wing surface, aspect ratio, flapping amplitude, lift coefficient, and wing loading have much effect on the FWAV wing design (Nan et al., 2018). FWAVs are usually divided into three categories, i.e. micro-, nano-, and pico-aerial vehicles (Hassanalian et al., 2017a). In this article, an attempt has been made to explain the development of FWAV in a systematic manner. Various aspects related to FWAV have also been comprehensively reviewed.

2. Flapping Wing Micro Aerial Vehicles

The micro aerial vehicle (MAV) is a UAV which can take off with a maximum weight of 5 kg. It can hover uninterruptedly for 1 hour in an operative range of 10 km (Petricca et al., 2011). The reported length of conventional MAVs are usually up to 50 cm long, weight 500 g (Hassanalian et al., 2017a), and their speed ranges from 30-60 km/h. The design of the flapping wing micro aerial vehicle (FWMAV) is primarily motivated from the birds. They are mainly used in strategic, military, and civilian purposes. When an object moves in the Earth atmosphere, the configuration of the gases surrounding it is affected, resulting in the formation of aerodynamic forces. The magnitude of these aerodynamic forces depends not only on the size, weight, and speed of the object but also the viscosity, stickiness and compressibility of the atmospheric gases. The process of producing aerodynamic forces by viscosity is a very complex process, which is generally explained by considering the Reynolds number. As a result, complete control over MAV flight is possible owing to low Reynolds number. In addition, its small structure also possesses high structural strength, decreased stall speed, and low inertia. In FWMAV flight, wing movement frequency and flexible air foils are two critical attributes. It cannot glide but is able to swing by changing the size of the wing during the flapping cycle. This process closely resembles the flying mechanism of small birds or insects. The flapping and flexible wing mechanism is able to overpower the deteriorating aerodynamic situation arises in steady flow conditions (Shyy et al., 1999). The most famous example of FWMAV is Robo Raven, and its picture is shown in Figure 1 (Gerdes et al., 2014). In another study, Gerdes et al. (Gerdes et al., 2015) increased the wing size of the Robo Raven and named it Robo Raven II. Flight test of Robo Raven II exhibited higher payload carrying capability than the original one. Holness et al. (Holness et al., 2015) demonstrated and studied the flying capability of a propeller-assisted Robo Raven. This modified Robo Raven flew successfully with the help of Propeller. It was also exhibited that it could generate more force for better aerodynamic performance. The payload capacity was also increased from 40 g to 81.1 g at 20% motor power. Perez-Rosado et al. (Perez-Rosado et al., 2016) redesigned Robo Raven and integrated thin solar cells on wings, tail and body to increase its flying capability. Their redesigned Robo Raven produced 64% more energy than the older one, and its flight time was 46% higher.

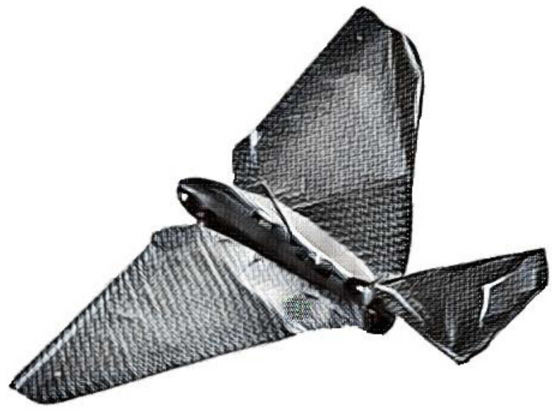

Figure 1. Flapping wing micro aerial vehicle (Robo Raven (Gerdes et al., 2014))

Zdunich et al. (Zdunich et al., 2007) described about a FWMAV developed by the Defence Advanced Research Projects Agency (DARPA) in 1997. They prepared two prototypes of FWMAV powered by IC engine and electric motor, respectively. The design and mechanical simulation of this prototype were primarily inspired by the flight of hummingbird with two additional wings. Both the prototype was successful hovered along with horizontal flight. Jones et al. (Jones et al., 2005) developed and experimented a flapping wing-propelled MAV. In this model the wingspan was 25 cm, the length of the aerial vehicle was 18 cm, and the weight was only 12.4 gm. The battery used to run it was able to fly this aerial vehicle for 15 to 20 minutes. They achieved a speed of 7 km/h to 18 km/h from this model, and this model was virtually stall-proof too. Nan et al. (Nan et al., 2017) worked on the optimization of the flexible wings of FWMAV. They found the camber angle and aspect ratio was a critical parameter for force production. A trapezoidal shaped wing with an aspect ratio of 9.3, weight of 17.2 g and straight leading edge gave the best performance under the designated settings. Bluman et al. (Bluman et al., 2018) said that one approach of hover control could not perform better than the other at all time, but they feel that sliding-mode control strategies can work much better than others. By this method, the appropriate control inputs can be found quickly despite slightly smaller intercycle variation, and the effect of wind gusts can be corrected promptly. Truong et al. (Van Truong et al., 2018) presented structural optimisation especially the gearbox of FWMAV. They proposed topological modifications on spur gear and motor holder and conducted numerical analysis to ensure weight saving and stiffness enhancement of the structure. The changes suggested by them reduced a significant amount of weight and improved structural stiffness of gearbox than the original one at similar loading conditions. Lu et al. (Lu et al., 2018) tried to obtain the best wing configuration for FWMAV to get the least noise per thrust. They swapped the material but did not make any changes to the basic geometry of the wings. They observed that wings made from dielectric elastomer were 13 dBA quieter than the commonly used Mylar wings and produced 3 dBA/g less noise per thrust. Jitsukawa et al. (Jitsukawa et al., 2017) had designed and analysed the wing folding mechanism for FWMAV. On the evaluation of generated forces, it was revealed that enough force could be achieved for wing movement, but the thrust was not sufficient to lift the MAV. According to them redesigning the wing mechanism and reduced weight of MAV could be a solution to this problem.

2. Flapping Wing Nano Aerial Vehicles

The research and development of Nano aerial vehicles (NAV) are gaining importance due to its usefulness in intelligence missions or surveillance. The design of NAV flapping wings is inspired by very small birds (such as hummingbirds) and giant insects (such as dragonflies). When NAVs is equipped with sophisticated sensors, they are able to work in adverse conditions and also in confined space. This NAV must be able to take off with a maximum weight of 25 g. It should also be able to hover at an altitude of 100 m continuously for less than one hour in an operative range of 1 km. Ideally, the wingspan of a conventional NAV should not be greater than 15 cm. Its minimum weight should be up to 20 g without any payload (Petricca et al., 2011). Keennon et al. (Keennon et al., 2012) developed a flapping wing nano aerial vehicles (FWNAV) named Nano Hummingbird. It had a wing length of 7.4 cm, and it was able to hover at a 24.12 km/h speed. The flipping frequency of the wings were 30 Hz. However, the weight of this mechanical hummingbird (shown in Figure 2) was 19 g, which was more than the weight of biological hummingbirds.

Figure 2. Nano Humming bird designed by (Keennon et al., 2012)

Ghommem et al. (Ghommem et al., 2019) manufactured a hover-capable biplane FWNAV. The wingspan and weight of their prototype were 24 cm and 15 g, respectively. The wings of FWNAV were powered by Li-Po battery, and it was able to flap in 20-47 Hz frequency. In this design, the wings were elliptical trailing edge type. A thin Mylar film and thin carbon rod were used to fabricate the wings. Bontemps et al. (Bontemps et al., 2012) prepared an insect-inspired FWNAV. They incorporated indirect actuation controlled resonant wing concept in their design. Owing to that system, large bending angles, passive wing torsion, and minimum power consumption were expected. The body of FWNAV prototype was built from a polymer material, in which an electromagnetic actuator was installed to obtain passive wing torsion under control vibrational amplitude. The wingspan and weight of this prototype was 3.5 cm and 22 mg, respectively. In addition to that, the bending angle of wings was 60°. Hassanalian et al. (Hassanalian et al., 2017b) studied the effect of wing shape and its kinematics on the performance of FWNAV. They found that for similar wingspan and surface area, honeybee and bumblebee type wings provided optimum results for forward flight of FWNAV. In another study, Hassanalian et al. (Hassanalian et al., 2017c) reported that the best wing shape for forward flight of FWNAV was inspired by the wing shape of a cicada insect. On the other hand, Throneberry et al. (Throneberry et al., 2017) studied the wings shape of various insects in order to determine the best wing shape for hovering operation of FWNAV. They discovered that twisted parasite wing shape was the best suitable choice for FWNAV application. Mateti et al. (Mateti et al., 2009) prepared a clapping wing NAV. A clapping wing air vehicle is inspired by the insects whose wings touch each other during flapping while flying. In this new clapping wing NAV, piezoelectric T-beam actuators were used as a source of energy for the flap motion of wings. The large angular response of the wings was obtained by amplifying the small stress produced by PZT, which was accomplished by hinge and lever mechanism. The desired range of wing motion at a wingstroke of 45° was obtained at 1 Hz.

3. Flapping Wing Pico Aerial Vehicles

The design of Pico aerial vehicle (PAV) flapping wings is greatly inspired by the wings of small flying insects like bees, flies, mosquitoes, etc. The maximum take-off weight capacity of the PAV is 500 mg, and all its dimensions are not exceeding 5 cm. The most recent example of flapping wing pico aerial vehicle (FWPAV) is "RoboBee" developed at Harvard University is shown in Figure 3 (Wood et al., 2012, 2017). Mateti et al. (Mateti et al., 2013) developed a naval flapping wing mechanism for FWPAV. It was manufactured by a dried film of epoxy-based negative photoresist using the photolithography technique. They named it LionFly and its power source was piezoelectric (PZT-5H) bimorph actuator. It was observed that the resonance frequency of this PAV prototype was 49.13±1.43 Hz and peak to peak flapping angle was 75 °. Zhang et al. (Zhang et al., 2017) demonstrated an integrated system-on-chip for bee sized FWPAV. It is a self-contained chip that could be operated directly with Li-ion batteries. Better performance and low energy consumption were reported after using this system-on-chip in FWPAV.

Figure 3. Pico aerial vehicle (RoboBee (Wood et al., 2013))

4. Conclusion

Flapping wing aerial vehicles are a new and advanced entrant in the aviation field which can be utilized to execute simple or complex operations with ease without any human casualties. A better lift can be obtained from the flapping wing mechanism compared to fixed wing mechanism, and a further increase in lift is possible without increasing flight speed. In this work, an effort has been made to highlight the research and development attempts in the area of FWAV recently. It was observed that more research is being conducted on flapping-wing micro aerial vehicles compared to Nano and Pico aerial vehicles because its construction process is relatively simple and its use is practically possible. Flapping wing MAVs are best suited for gliding operation whereas flapping wing PAVs are best for hovering. To provide power to Micro, Nano and Pico Aerial Vehicles, various means such as batteries, small IC engines, propellers, PZTs etc. were employed. In some research, solar cells were also integrated into the flapping wing aerial vehicles as an alternative energy resource. The efficiency and flying duration of flapping wing aerial vehicles can be enhanced by the utilisation of alternative energy resource with the main energy source. Efforts are also being made to mimic the wing shape of naturally flying creatures to increase the efficiency of these aerial vehicles. These attempts were mainly performed for FWNAVs and FWPAVs. The effects of materials used on the performance of aerial vehicles were also investigated in some studies. Advanced polymer based materials is gaining importance due to their light weight, durability, molding capability etc. It can be said that there is still a lot of research required for this field to be fully developed.

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