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Research progress on the energy consumption of bionic flapping-wing aerial vehicles

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ABSTRACT

Natural flyers use muscles, bones, and other structures in coordination to attain agile and nimble flight performance. They can fly in various complex environments through different flight modes, such as flapping, hovering, and gliding. The high-lift mechanism on flapping-wing flights plays a fundamental role in bionic flapping-wing aerial vehicle design. Bionic flapping-wing aerial vehicles operate in modes that mimic birds and insects. They rely on flapping wings to generate the lift and thrust required for flight. With the advantages of good concealment, high energy efficiency, and low flying noise, flapping-wing aerial vehicles have great potential in performing civil and military tasks. In the civil field, they can go deep into different complicated, unknown environments and perform environmental monitoring, rescue missions, and other special tasks that are difficult for human beings to complete. In the military field, they can replace human beings to complete covert reconnaissance and search tasks and play an important role in maintaining regional stability and preventing military invasions. Because of their broad application prospects, flapping-wing aerial vehicles have drawn considerable attention from researchers. Inspiration from the distinct features of natural flyers has influenced flapping-wing aerial vehicle design. Many attempts have been made to improve flapping-wing aerial vehicle performance. Because flapping-wing aerial vehicles have a small payload, they carry large-capacity batteries with difficulty, resulting in limited endurance. Under limited energy, the endurance time of flapping-wing aerial vehicles can be effectively increased by reducing energy consumption. An important research direction of flapping-wing aerial vehicles is to improve endurance by developing high energy density batteries and bionic design. Starting from bionic mechanism analysis, mechanism optimization design, and control strategy research, designers and engineers have conducted much research on the energy consumption of flapping-wing aerial vehicles, and achievements have been made frequently. However, their flight efficiency is still far from their natural counterparts. Many challenges remain in the bionic mechanism, fabrication, and autonomous flight of flapping-wing aerial vehicles. This paper summarizes the research progress on the energy consumption of bionic flapping-wing aerial vehicles. We discuss the main components of flapping-wing aerial vehicle energy consumption. Then, we analyze the effects of static parameters, dynamic parameters, and control strategies on the energy consumption of flapping-wing aerial vehicles. The energy consumption improvements of flapping-wing aerial vehicles with different parameter designs are compared. Finally, we propose measures to reduce energy consumption and discuss future research directions.

KEYWORDS:
flapping-wing aerial vehicle, natural flyer, flight mode, energy consumption, bionic design

1. Introduction

Human beings' original dream of flying originated from imitating flying creatures such as birds and insects in nature. According to the aerodynamic layout and the source of flight power, common aircraft can be divided into three categories: fixed-wing aircraft, rotorcraft and flapping-wing aircraft. Fixed-wing aircraft cannot achieve the hovering function, and it is difficult to provide sufficient lift after the wings are miniaturized; rotorcraft has the ability to hover, but the flight efficiency will drop rapidly as the diameter of the rotor system decreases[1]; flapping-wing aircraft adopts bionic flight mode and has a wide range of application prospects in military and civilian fields[2]. It has attracted the attention of researchers due to its potential high flight efficiency.

In recent years, with the development of high-tech technologies such as microelectronics, smart materials, and precision machining, the research on bionic flapping-wing aircraft has made great progress. Representative research results abroad include the "RoboBee" series prototypes of the Wood team at Harvard University [3-6], the "DelFly" series prototypes of the Karásek team at Delft University of Technology [7- 9], the "KUBettle" series prototypes of the Park team at Konkuk University [10- 12], The “Phoenix” of MIT[13], the “E-Flap” of the University of Seville[14], the “BionicSwift” of Festo, the “SmartBird” of Festo, the “eMotionButterflies” of Festo, the “BionicOpter” of Festo, and the “Nano Hummingbird” of AeroVironment [16]. Representative domestic research results include the “USTBird” [17- 20] and the “USTButterfly-S” [21] of He Wei’s team at the University of Science and Technology Beijing, the “Dove” [22] of Song Bifeng’s team at Northwestern Polytechnical University, and the “Phoenix” [23] of Xu Wenfu’s team at Harbin Institute of Technology (Shenzhen). “HIT-Hawk” and “HIT-Phoenix” [23], the bionic butterfly “X-Butterfly” [24] by Wang Shaoping’s team at Beijing University of Aeronautics and Astronautics, and the insect-like micro flapping-wing aircraft [25], [26] by Zhang Weiping’s team at Shanghai Jiaotong University. Although bionic flapping-wing aircraft have made great breakthroughs in prototype development, there is still a big gap between them and the practical level of prototypes. The biggest problem is the insufficient endurance. The load capacity of bionic flapping-wing aircraft is limited, which puts strict requirements on the weight and size of the battery. Since it is still difficult to develop high-energy density batteries that meet the requirements at this stage, the best way is to “learn from nature” and reduce energy consumption through bionic design to increase endurance. This paper summarizes and analyzes the characteristics of efficient flight of flying organisms in nature, discusses the current research status of energy consumption of bionic flapping-wing aircraft, summarizes and prospects the development trend of efficient bionic design of flapping-wing aircraft, and hopes to provide guiding suggestions for the design of bionic flapping-wing aircraft.

2. Research on energy consumption of flying organisms

Bionic flapping-wing aircraft are a type of aircraft designed with inspiration from flying organisms in nature [27]. Therefore, before studying the energy consumption of bionic flapping-wing aircraft, it is helpful to summarize and organize the current research on energy consumption of birds and insects to analyze the energy consumption of bionic flapping-wing aircraft. All flying organisms in nature, without exception, use flapping wings to fly. They only need to take less food to fly a long distance, and their own wing structure and flight strategy play a very critical role.

The structure of bird wings is very complex. The entire wing is covered by primary flight feathers, secondary flight feathers, coverts and down feathers, and can generally be divided into two sections - the inner wing and the outer wing, as shown in Figure 1(a). The wing shapes of different birds are generally different, which also leads to different flight characteristics. For example, the wings of Columbiformes and Passeriformes are generally elliptical, with wide hind wings, strong maneuverability, and can take off quickly, but they generally need to flap their wings continuously during flight, which is not conducive to long-distance flight; the wings of Strigiformes are generally long and wide, and the gaps between their primary flight feathers are large, which can easily break up the airflow, allowing them to make good use of the airflow to soar; the wings of Passeriformes are slender and can fly quickly; long and slender wings are often seen in some large birds such as albatrosses and herring gulls. These birds generally have strong maneuverability and endurance, and can actively use airflow to glide long distances [28]. Unlike bird wings that evolved from forelimbs, Insect wings are mostly formed by the dorsal plate of the body segment extending to both sides, and the wing structure is simpler than that of birds, generally consisting of only crisscrossed thin wing veins with a certain degree of rigidity and a thin wing membrane with a certain degree of toughness [29], as shown in Figure 1 (b). In addition to a few nerves, the wings of insects are only connected to the body by muscles at the root of the wing, and do not have a skeletal and muscle system.

3. Conclusion

Starting from the flying creatures in nature, this paper summarizes some characteristics of flying creatures in nature with efficient flight ability, as well as the research progress on the impact of these characteristics on the endurance of flapping-wing aircraft, which provides some references for improving the endurance of flapping-wing aircraft. For traditional rotor and fixed-wing aircraft, their technologies are relatively mature, and they can extend the endurance through optimized design and energy recovery. However, the current research on bionic flapping-wing aircraft is still in the simple imitation of flying creatures in nature, and some theories and models are still inaccurate. In the case that battery material technology and load-bearing capacity cannot make major breakthroughs in a short period of time, the influence of various parameters on the energy consumption of flapping-wing aircraft through bionic design, and then optimizing various design parameters, as well as finding suitable energy recovery and auxiliary power supply systems are important directions for improving the endurance of bionic flapping-wing aircraft in the future.

4. References

[1] Ramasamy M, Lee T E, Leishman J G. Flow field of a rotating-wing micro air vehicle. J Aircr, 2007, 44(4): 1236 doi: 10.2514/1.26415

[2] He W, Ding S Q, Sun C Y. Research progress on modeling and control of flapping-wing air vehicles. Acta Autom Sin, 2017, 43(5): 685 doi: 10.16383/j.aas.2017.c160581

[3] Ma K Y, Chirarattananon P, Fuller S B, et al. Controlled flight of a biologically inspired, insect-scale robot. Science, 2013, 340(6132): 603 doi: 10.1126/science.1231806

[4] Graule M A, Chirarattananon P, Fuller S B, et al. Perching and takeoff of a robotic insect on overhangs using switchable electrostatic adhesion. Science, 2016, 352(6288): 978 doi: 10.1126/science.aaf1092

[5] Chen Y F, Wang H Q, Helbling E F, et al. A biologically inspired, flapping-wing, hybrid aerial-aquatic microrobot. Sci Robot, 2017, 2(11): eaao5619 doi: 10.1126/scirobotics.aao5619

[6] Jafferis N T, Helbling E F, Karpelson M, et al. Untethered flight of an insect-sized flapping-wing microscale aerial vehicle. Nature, 2019, 570(7762): 491 doi: 10.1038/s41586-019-1322-0

[7] De Croon G C, De Clercq K M, Ruijsink R, et al. Design, aerodynamics, and vision-based control of the DelFly. Int J Micro Air Veh, 2009, 1(2): 71 doi: 10.1260/175682909789498288

[8] Scheper K Y W, Karásek M, Wagter C D, et al. First autonomous multi-room exploration with an insect-inspired flapping wing vehicle // 2018 IEEE International Conference on Robotics and Automation. Brisbane, 2018: 5546

[9] Karásek M, Muijres F T, De Wagter C, et al. A tailless aerial robotic flapper reveals that flies use torque coupling in rapid banked turns. Science, 2018, 361(6407): 1089 doi: 10.1126/science.aat0350

[10] Phan H V, Kang T, Park H C. Design and stable flight of a 21g insect-like tailless flapping wing micro air vehicle with angular rates feedback control. Bioinspir Biomim, 2017, 12(3): 036006 doi: 10.1088/1748-3190/aa65db

[11] Phan H V, Aurecianus S, Kang T, et al. KUBeetle-S: An insect-like, tailless, hover-capable robot that can fly with a low-torque control mechanism. Int J Micro Air Veh, 2019, 11: 1756829319861371

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

[13] Jackowski Z J. Design and Construction of an Autonomous Ornithopter [Dissertation]. Cambridge: Massachusetts Institute of Technology, 2009

[14] Zufferey R, Tormo-Barbero J, Guzmán M M, et al. Design of the high-payload flapping wing robot E-flap. IEEE Robotics Autom Lett, 2021, 6(2): 3097 doi: 10.1109/LRA.2021.3061373

[15] Send W, Fischer M, Jebens K, et al. Artificial hinged-wing bird with active torsion and partially linear kinematics // 28th International Congress of the Aeronautical Sciences. Brisbane, 2012: 1

[16] Keennon M, Klingebiel K, Won H. Development of the nano hummingbird: A tailless flapping wing micro air vehicle // 50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition. Nashville, 2012: 588

[17] He W, Liu S P, Huang H F, et al. System design and experiment of an independently driven bird-like flapping-wing robot. Control Theory Appl, 2022, 39(1): 12 doi: 10.7641/CTA.2021.00394

[18] Fu Q, Wang X Q, Zou Y, et al. A miniature video stabilization system for flapping-wing aerial vehicles. Guid Navigat Control, 2022, 2(1): 2250001 doi: 10.1142/S2737480722500017

[19] Huang H F, He W, Wang J B, et al. An all servo-driven bird-like flapping-wing aerial robot capable of autonomous flight. IEEE/ ASME Trans Mech, 2022, http://dx.doi.org/10.1109/TMECH.2022.3182418

[20] He W, Mu X X, Zhang L, et al. Modeling and trajectory tracking control for flapping-wing micro aerial vehicles. IEEE/CAA J Automatic Sin, 2020, 8(1): 148

[21] Huang H F, He W, Zou Y, et al. System design and control of a butterfly-inspired flapping-wing aerial robot based on wire-driven steering. Control Theory Appl, http://kns.cnki.net/kcms/detail/44.1240.TP.20211117.1454.048.html

[22] Yang W Q, Wang L G, Song B F. Dove: A biomimetic flapping-wing micro air vehicle. Int J Micro Air Veh, 2018, 10(1): 70 doi: 10.1177/1756829317734837

[23] Pan E Z, Xu H, Yuan H, et al. HIT-Hawk and HIT-Phoenix: Two kinds of flapping-wing flying robotic birds with wingspans beyond 2 meters. Biomim Intell Robotics, 2021, 1: 100002 doi: 10.1016/j.birob.2021.100002

[24] Zhang Y X, Wang X J, Wang S P, et al. Mechanism of butterfly forward flight and prototype

verification based on characteristic motion observation. J Beijing Univ Aeronaut Astronaut, https://kns.cnki.net/kcms/detail/11.2625.V.20210913.1521.002.html

[25] Chi P C, Zhang W P, Chen W Y, et al. Design and fabrication of an SU-8 biomimetic flapping-wing micro air vehicle by MEMS technology. Robot, 2011, 33(3): 366 doi: 10.3724/SP.J.1218.2011.00366

[26] Zou Y, Zhang W P, Ke X J, et al. The design and microfabrication of a sub 100 Mg insect-scale flapping-wing robot. Micro Nano Lett, 2017, 12(5): 297 doi: 10.1049/mnl.2016.0687

[27] Fu Q, Zhang X, Zhao M, et al. Research progress on the wind tunnel experiment of a bionic flapping-wing aerial vehicle. Chin J Eng, 2022, 44(4): 767

[28] Cai C R. Study on Aerodynamic Performance of Bionic Wing Based on Carrier Pigeon Wing [Dissertation]. Changchun: Jilin University, 2018

[29] Liu L. The Design Technologies of Biomimetic Wings for Flapping-Wing MAVs [Dissertation]. Xi'an: Northwestern Polytechnical University, 2007

[30] Wu J C, Popovi Z. Realistic modeling of bird flight animations. Acm Trans Graph, 2003, 22(3): 888 doi: 10.1145/882262.882360

[31] Bajec I L, Heppner F H. Organized flight in birds. Animal Behav, 2009, 78(4): 777 doi: 10.1016/j.anbehav.2009.07.007

[32] Yang Y G, Su H P, Gu X D, et al. Numerical simulation analysis of the effects of flight angle and bend-fold on bird-like flapping-wing air vehicle. J Syst Simul, 2018, 30(5): 1781 doi: 10.16182/j.issn1004731x.joss.201805020