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Effect of motion trajectory on the aerodynamic performance of a flapping airfoil

Shuchao Yang [b], Chen Liu [b], Jie Wu [a,b,*]

[a] State Key Laboratory of Mechanics and Control of Mechanical Structures, Nanjing University of Aeronautics and Astronautics, Yudao Street 29, Nanjing, Jiangsu 210016, China

[b] Department of Aerodynamics, Nanjing University of Aeronautics and Astronautics, Yudao Street 29, Nanjing, Jiangsu 210016, China

HIGHLIGHTS

- A surging motion is added to the traditional motion of a flapping airfoil.
- Thrust and lift forces can be improved under specific condition.
- Two-circle motion model is helpful for propulsive efficiency enhancement.

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ABSTRACT

In this paper, the influence of the motion trajectory on the aerodynamic performance of a flapping airfoil is numerically investigated. The airfoil synchronously performs a rotating motion (pitch), a horizontal motion (surge) and a vertical motion (plunge). The motion trajectory can be modified by changing the relative frequency of surging motion (k), the amplitude of surging motion (l_m) and the phase difference between pitch and surge (φ). To perform the numerical simulations, a NACA0012 airfoil is employed. A low Reynolds number (Re $=$ 500) is selected for small creatures and flapping MAVs. As compared with the traditional motion, it is observed that the figure-of-eight motion trajectory has a promotion for the thrust and propulsive efficiency, and the lift is improved when the relative surging frequency k is an odd number with the specified phase difference. In addition, the phenomenon of multiple vortices and resultant vortex capture appears when the surging motion is added, which is helpful for the improvement of thrust.

1. Introduction

The development of micro aerial vehicles (MAVs) and nano aerial vehicles (NAVs) has attracted a great number of researches recently, because of their importance in both theory development and practical applications. Actually, the inventions of MAVs and NAVs are inspired from insects, birds and swimming animals that utilize flapping wings motion as a mode of propulsion in air or water (Rozhdestvenshy and Ryzhov, 2003). Therefore, the use of flapping wings systems shows great promise and prospect in locomotion applications. The early studies of flapping wings for propulsion were mainly

* Corresponding author.
E-mail address: wuj@nuaa.edu.cn (J. Wu).

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performed through theoretical analysis (Garrick, 1936). Later, more and more investigations on flapping wings systems were completed by both experiments and numerical simulations (Jones et al., 1998; Triantafyllou et al., 2004). However, owing to the complexity of the flow field and fluid–structure interactions involved in the flapping motion, there is still tremendous room for exploring how to make such systems more efficient.

Up to now, to achieve the enhancement of both thrust and the corresponding propulsive efficiency of flapping wings systems, a great deal of effort has been devoted and a large number of techniques have been employed. Tian et al. (2012) put forward a novel strategy by introducing a traveling-wave motion into the surface of a foil. It was found that the larger propulsive efficiency could be achieved as compared with most aquatic animals, which may lead to an important design capability for underwater vehicles. Mivehchi et al. (2016) experimentally investigated the ground effect and found that the distance between the ground and the flapping foil has a significant impact on the thrust force. Meanwhile, the propulsive efficiency is increased slightly when the foil operates near the ground. Broering and Lian (2015) numerically studied the vortex interactions of tandem flapping wings. It was indicated that zero phase lag could increase the size of the leading edge vortex (LEV) generated by the hindwing and the resulting thrust production. Lee and Lee (2013), Lee et al. (2015) analyzed the mechanism of a flapping foil moving with a propulsive velocity. They announced that the symmetric rotation produced a better propulsion velocity with less fluctuation as compared with the advanced rotation and delay rotation. Lu et al. (2013) concluded that large pitching amplitude generates much more thrust than the lower pitching amplitude. However, when the pitching amplitude exceeds some specified limit, the thrust increases slowly and the propulsive efficiency declines noticeably. Tian et al. (2016) studied the effect of pitch–pivot-point location, and they pointed out that the rotating axis position affects the evolution of unsteady wake vortices and propulsive performance. It can be explained that by moving the pitch–pivot-point of pitching foil can be considered as adding a plunging motion to the original pitching motion. Ashraf et al. (2011) proved that the rate of thrust improvement is much better when the plunging amplitude is lower, and the performance of thin airfoils outperforms thick airfoils.

Besides the above mentioned researches, many other studies have been focused on the lift enhancement of the flapping foil. Mantia and Dabnichki (2012) illustrated that the lift force generated by flapping wing increases sharply when the added mass contribution is considered. Young and Lai (2004) demonstrated that leading-edge effects are of great importance in determining the forces, whereas the trailing-edge effects influence primarily on wake structures. They also found that the lift force strongly depends on oscillation frequency. Sarkar et al. (2013) evaluated the effects of asymmetric kinematics on the lift enhancement capabilities of a flapping foil during hover. The normal hover shows a significant increase in the average lift value compared with the sinusoidal hover, and a large amount of lift can be generated during the faster stroke for the sinusoidal hover. Amiralaei et al. (2010) revealed that unsteady parameters such as oscillating amplitude, reduced frequency and Reynolds number play a great role in the development of the maximum lift value, strength and numbers of the generated vortices, and even the surrounding flow structures.

In addition, some attention has also been paid to the effect of camber and flexible airfoil on the aerodynamic performance. Hoke et al. (2015) indicated that varying camber provides little improvement in thrust and propulsive efficiency, but the interactions between LEV and foil curvature result in great propulsive forces. Jaworski and Gordnier (2015) concluded that the maximum of thrust and propulsive efficiency are obtained when the membrane pressure is changed, and it was found that the vortices can interact favorably with the local membrane camber to enhance the propulsive force. Tian et al. (2013) found that the passive pitching motion of a flexible wing can significantly increases thrust and maintain lift at the same level or increase it synchronously.

As discussed above, great progress has been made in the propulsive characteristics of flapping wings systems. However, up to date, there is still limited attention paid to the effect of motion trajectory on the aerodynamic performance of flapping foil. Only few examples can be found in the literature. Sarkar and Venkatraman (2005) studied the effect of three motion modes for propulsive performance: asymmetric motion, sinusoidal motion and constant heave rate oscillations motion. They pointed out that both asymmetric motion and a train of sinusoidal pulses motion give better thrust and propulsive efficiency in comparison to sinusoidal motion. However, constant rate heave motion does not compare favorably with traditional harmonic motion. Amiralaei et al. (2011) performed a modified figure-of-eight-like flapping pattern by using a thin ellipsoidal geometry. It was found that the parameters change the instantaneous force coefficients quantitatively and qualitatively. Esfahani et al. (2015) investigated the effect of elliptical motion trajectory on the flapping airfoil. It was noted that motion trajectories change both the effective angle of attack and the vortex shedding pattern. As a result, they influence significantly the aerodynamic and propulsive performance.

Therefore, to further explore mechanics of a flapping foil, this work continues to investigate the effect of motion trajectory of a flapping airfoil on the propulsive performance and lift enhancement as well. A NACA0012 airfoil, which is placed in a two-dimensional laminar flow, synchronously executes a combined periodic pitching, surging (forwards/backwards) and plunging (upwards/downwards) motion. After selecting the Reynolds number and plunging amplitude, the effects of pitching amplitude, surging amplitude, location of pitch–pivot-point, phase difference between pitch and surge as well as surging frequency on the aerodynamic performance are numerically examined in detail. Based on the numerical results obtained, the thrust and lift coefficients, propulsive efficiency as well as the vorticity and pressure coefficient contours are meticulously analyzed.