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Effect of unequal flapping frequencies on flow structures

Idil Fenercioglu*, Oksan Cetiner

Department of Astronautical Engineering, Istanbul Technical University, Maslak-Ayazaga, Istanbul 34469, Turkey

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ABSTRACT

The effects of unequal pitching and plunging frequency on the flow structures around a flapping airfoil is investigated using the Digital Particle Image Velocimetry (DPIV) technique in the reduced frequency range of $0.31 \leqslant k \leqslant 6.26$ corresponding to Strouhal number range of $0.1 \leqslant St \leqslant 1.0$. The SD7003 airfoil model undergoes a combined flapping motion where the pitch leads the plunge with a phase angle of 90° in a steady current. The investigated cases are classified into five flow structure categories based on instantaneous and averaged vorticity patterns and velocity fields around and in the near-wake of the airfoil while the frequency of plunging motion was kept the same as the frequency of pitching motion. Example cases for each category were then investigated for unequal pitching and plunging frequencies and it is observed that employing unequal pitching and plunging frequencies for an oscillating airfoil may result in a change of flow structure category.

1. Introduction

Biological inspiration offers a means to enhance the performance of the next generation of small-scale air vehicles over existing fixed and rotary wing systems. Many insects carry large amounts of payload despite their small and fragile wings, yet they are capable of easily performing maneuvers with rapid accelerations and decelerations. There are an increasing number of researchers and groups building a flapper (Jones et al. [21], de Croon et al. [10], etc.) and attempting to quantify the relative performance merits of those Micro Air Vehicles (MAVs) (Groen et al. [15], Maniar et al. [33], Kim et al. [25]).

Fundamental research in this area has received great interest in the past years and investigations are still widely under progress in order to find out if biomimetics is an effective solution to MAVs. The generation of thrust by an oscillating airfoil is known for quite a long time as summarized by Jones et al. [19] and although the basic mechanisms of thrust production are understood, the effectiveness of thrust production and its enhancement through several variants are still under investigation.

The earliest theories concerning flapping wing flight were related to purely heaving airfoils. In their independent studies, Knoller [26] and Betz [3] were among the first to observe that a flapping wing generates an effective angle of attack, resulting in an aerodynamic force that includes both cross-stream and streamwise components and their theory was experimentally confirmed by Katzmayer [24]. Birnbaum [4] applied Prandtl's [41] unsteady thin airfoil theory to quantitatively predict the thrust generation of plunging airfoils. He was also the first to introduce a dimensionless similarity parameter named as the reduced frequency, which characterizes the oscillation behavior as the ratio between the flapping velocity and forward flight velocity [40]. In 1935, von Kármán and Burgers [49] experimentally observed the generation of a reverse vortex street and its corresponding jet like average velocity profile which have been associated with the thrust development on a flapping airfoil in an incompressible flow. Theodorsen [44] derived a theory for a thin flat plate with simple harmonic oscillations in incompressible uniform flow and showed that the circulatory lift was a function of the reduced frequency. Garrick [14] and von Kármán and Sears [50] were among the others to conduct theoretical analyses on pitching and plunging airfoils in forward flight. By the end of the century, the vortical signatures of oscillating airfoils had been investigated by many researchers (Jones et al. [22], Lai and Platzer [31] and Rival and Tropea [43]). Jones and Platzer [18] summarized the numerical and experimental investigations that led them to develop their flapping-wing micro air vehicle. Cleaver et al. [8] showed that a sinusoidally plunging airfoil can create lift improvement due to convection and that the interaction of the trailing edge vortices with the leading-edge vortex on the upper surface.

Since pure pitching airfoils are also a popular topic for helicopter rotor performance, some studies describe dynamic features associated with incidence variations of sinusoidally pitching airfoils for prediction of dynamic stall (Kramer [29], McCroskey [34] and Carr [7]). Thrust generation by pure pitching was experimentally

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* Corresponding author. Tel.: +90 (212) 285 3145.
E-mail address: fenercio@itu.edu.tr (I. Fenercioglu).

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demonstrated by Koochesfahani [27] and it was shown that by controlling the frequency, amplitude and the shape of oscillation waveform, the structure of the wake can also be controlled. Panda and Zaman [38] investigated the wake surveys to estimate lift and observed that a vortex originates from the tailing edge just when dynamic stall vortex is shed and they referred to this kind of opposite signed vortex pair as a 'mushroom' wake. The vorticity convection and the shedding of vortices in the near wake were investigated by many others (Kuo and Hsieh [30] and Jung and Park [23]).

In a review of experimental biomimetic studies by Triantafyllou et al. [46], the similar mechanisms of force production and flow manipulation in fish and birds were classified, noting that the conditions of swimming are different from flying. Pure heaving or plunging motion is mostly employed by large animals like birds and fish operating in the low frequency regime at larger Reynolds numbers, and insects typically use the combination of plunging and pitching motions in low Reynolds number regime. Wang's [51] computational study also showed that pure plunging motion is not enough to generate thrust at low Reynolds numbers. Even though nearly all examples of flapping wing propulsions in nature combine both pitching and plunging, according to Jones et al. [20], the key parameter determining whether an airfoil creates thrust or extracts power from the flow is the effective angle of attack and its variation with the geometric angle of attack.

The parameter space for combined plunging and pitching motion includes the frequencies and amplitudes of pitching and plunging motions and the phase angle, ψ, between pitch and plunge. Anderson et al. [1] defined the conditions for optimal thrust production to operate at $0.25 < St < 0.4$; the values also match the range in which most fish operate at their maximum swimming velocities (Triantafyllou [45]), but the Strouhal number is also not enough to define the efficiency of oscillating foils [54]. Guglielmini and Blondeaux's [16] vorticity equation computations showed good agreement with Anderson et al.'s [1] experiments and they concluded that the high efficiency and thrust coefficients are related with the formation of a jet of fluid leaving the foil from the trailing edge. Recently, Bohl and Koochesfahani [5] worked on force estimation, studied the effect of velocity fluctuations in the integration of the momentum theorem for pure pitch oscillations and showed that the switch in the vortex array orientation does not coincide with the condition for crossover from drag to thrust.

The shedding of leading edge vortices and the use of dynamic stall process have shown to be key factors in lift generation of flapping wing mechanisms by Platzer and Jones [39]. The dynamic stall phenomenon for airfoils with combined pitching and plunging motions was also investigated by many researchers, for example, Isogai et al. [17] and Read et al. [42]. Recently, Baik et al. [2] studied experimentally the flow topology, leading-edge vortex dynamics and unsteady forces produced by pitching and plunging flat-plate aerofoils in forward flight.

Periodic motions of the airfoils which are more applicable to forward flight of MAV applications are more systematically studied in literature [40]. Earlier studies on non-periodic motion of airfoils, such as the pitch-up problem, mainly focused on fixed wing aircraft maneuvering applications (Visbal and Shang [48], Visbal [47], Koochesfahani and Vanco [28], Conger and Ramaprian [9] and Oshima and Ramaprian [37]). The advance in MAVs resulted in investigations of transient problems with higher rates of pitch-up motions more relevant to maneuvering, perching and gust response (Ol et al. [36], Garmann and Visbal [13] and Yu et al. [55]). The same canonical pitch-hold-return problem was also experimentally investigated by Buchner et al. [6] using both stereoscopic and tomographic PIV methods to gain some understanding of how three-dimensionality develops in such flows.

Although there are many experimental and numerical studies investigating flapping airfoils, effects of unequal oscillating frequencies of pitching and plunging motions received little attention and those unique investigations have not reached a conclusion as the problem becomes much more complex. Ol [35] briefly studied the oscillations of an SD7003 airfoil with different pitch and plunge frequencies. He considered a motion where the plunge frequency is half of the pitch frequency and observed that a separated leading edge vortex is formed every pitch period, unlike all the previously tested pure plunge cases. Webb et al. [52] also considered the effects of unequal pitch and plunge motion of an SD7003 airfoil, with various pitch pivot locations, to model the gust response with the lower-frequency motion where the higher-frequency motion is the kinematics of the flapping MAV. They considered results based on experiments at $Re = 10\,000$ and computations for $Re < 1000$, stating a similar vortex shedding behavior. For the case where the pitch frequency was twice the plunge frequency and the pitch pivot point was at half chord, they pointed out a discrepancy between experiment and computational results. Their flow visualization experiments with dye injection showed that placing the pivot point closer to downstream location resulted in the formation of a stronger leading edge vortex and they observed the reverse Karman vortex street when they switched to the standard case of equal pitch and plunge frequencies. Both studies leave many aspects unmentioned, hence the role of unequal oscillation frequencies on the formation of vortex structures and the production of lift and thrust are yet to be explored.

Motivated with practical applications to micro air vehicles with the size of small birds that flap wings, an experimental study is conducted using a pitching and plunging airfoil in steady water flow to observe the relationships between the flapping parameters and the related leading and trailing edge vortex formation. The investigated cases remain in the low Reynolds number range of $O(10^3)$–$O(10^4)$ which is of interest to the design and development of Micro Air Vehicle applications as also described in a recent study by Baik et al. [2].

The detailed quantitative evaluation of flow structures with instantaneous patterns of vorticity around and in the near-wake of a SD7003 airfoil model is previously obtained for a large parameter space for combined pitch and plunge motions in steady current (Fenercioglu and Cetiner [12] and Fenercioglu [11]) where the pitching frequency is set equal to the plunging frequency. The band of occurrence of flow structure categories on a k vs. h_{amp}/c plot agreed well with wake classification types presented in Jones et al. [22,19] for pure plunge motion.

The objective of this study is to explore the effect of using unequal oscillating frequencies for pitch and plunge motions in the near-wake of a two-dimensional wing. As the pitch amplitude and mean angle of attack are kept constant at moderate values as in the aforementioned baseline study, the plunge motion is expected to dictate the flow structures in the near-wake.

2. Experimental set-up

Experiments were performed in the close-circuit, free-surface, large scale water channel located in the Trisonic Laboratories at the Faculty of Aeronautics and Astronautics of Istanbul Technical University. The cross-sectional dimensions of the main test section are $1010\ \text{mm} \times 790\ \text{mm}$. The experiments are conducted at Reynolds numbers of $2500 \leqslant Re \leqslant 13\,700$ which simulate forward flight of small birds.

An SD7003 airfoil model, which is known to be optimized for low speed flows as indicated in studies of Windte et al. [53] and Lian and Shyy [32], is mounted in a vertical cantilevered arrangement in the water channel about its quarter chord. A rod connects the airfoil to the servo motor to provide a sinusoidal pitching