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Influence of thickness on performance characteristics of non-sinusoidal plunging motion of symmetric airfoil

R. Sankarasubramanian [a], Adithya Sridhar [a], M.S. Prashanth [a], Akram Mohammad [b], Ratna Kishore V. [a,*], V. Laxman [a]

[a] Department of Mechanical Engineering, Amrita School of Engineering, Amrita Vishwa Vidyapeetham, Coimbatore, India
[b] Department of Aeronautical Engineering, King Abdulaziz University, Jeddah, Saudi Arabia

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ABSTRACT

For the past few decades flapping wing aerodynamics has attracted a great deal of research interest from both the aeronautical and biological communities pertaining to the development of MAVs. The objective of this study is to examine and understand the effect of non-dimensional plunge amplitude and reduced frequency on propulsive performance of NACA 4-digit airfoil series and to examine the performance characteristics of square plunge motion and trapezoidal plunge motion. Two dimensional flow simulations around plunging symmetric aerofoils were performed using FLUENT. The simulations were carried out at Reynolds number of 20000 using incompressible laminar, NS solver. The reduced frequency (k) was varied from 0.5–5 and the plunging amplitude (h) was varied from 0.25–1.5. The plunging motions to the aerofoils were provided through UDFs. The effect of variation of k and h on the thrust coefficient (C_T), power-input coefficient (C_P) and propulsive efficiency (η) is studied. C_T value is maximum for square plunge profile for all the airfoils. However, for a given value of h, with the increase in k, C_T increases with increasing thickness of the airfoil and reaches a maximum value for airfoil thickness of NACA0018 and then starts decreasing. With varying h and k, it was observed that the propulsive efficiency reached a peak value and the peak shifts to higher h and k with increasing airfoil thickness. From the above study, it was concluded that airfoil thickness played a major part in influencing the thrust generation at low Strouhal number. However, at high Strouhal numbers airfoils showed diverse trends with respect to thrust generation. Sinusoidal plunging motion was more efficient but generated less thrust when compared to square and trapezoidal plunging motions.

1. Introduction

There has been a great interest in small sized radio controlled air vehicles also known as micro air vehicles (MAVs) since the early 20th century. Flapping wing aerodynamics has attracted a great deal of research interest recently from both the aeronautical and biological communities pertaining to the development of micro aero vehicles [27]. Such small crafts have the potential to be used as spies and scouts by defence organizations and can also be used for remote observation of environments inaccessible to ground vehicles. The aforementioned usages have led to numerous studies regarding the potential usage of oscillating airfoils for propulsion and lift in MAVs [28]. Early theoretical and experimental analyses [15,19,12] have shown that oscillating airfoils generate thrust at some particular oscillation frequency and plunge amplitude. Propulsive efficiency as a function of oscillation frequency was determined by Garrick [8], with the assumption of potential flow and small amplitude oscillation. Freymuth and others [7,13,20] have shown that oscillating airfoils can generate thrust during pure pitching or pure plunging motion. Based on the reduced frequency and plunge amplitude, the wakes of a plunging airfoil can be characterized as thrust-producing, neutral or drag-producing. Drag-producing wakes are characterized by a von Karman vortex street whereas thrust-producing wakes are characterized by a reverse von Karman vortex street. Based on these observations, numerous experiments and numerical analyses were carried out to study the effect of various parameters such as reduced frequency, Strouhal number and amplitude of an oscillating airfoil. Several numerical and experimental analyses were carried out in this field such as the dynamics of the wake and vortex rollup [14] and the dynamic stall phenomenon [5,6,11,21]. Kinsey and Dumas [17] showed that an oscillating symmetric airfoil can operate in two different regimes namely, propulsion and power extraction. In

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* Corresponding author.
E-mail address: ratnavk@gmail.com (R. Kishore V.).

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Nomenclature

c	chord length	m
t	time	s
f	frequency of oscillation	Hz
h	non-dimensional plunge amplitude; h_o/c	
k	reduced frequency; $\pi fc/U_\infty$	
L	lift force	N
D	drag force	N
Re	Reynolds number; $\rho U_\infty c/\mu$	
St	Strouhal number, $k.h$	
T	time-period of oscillation	s
Ω	angular frequency; $2\pi/T$	
η	efficiency; $C_{T,mean}/C_{P,mean}$	
V_y	plunge velocity	m/s
k_p	waveform frequency	
U_∞	free stream velocity	m/s
h_o	plunge amplitude	m
C_D	drag coefficient; $D/(0.5\rho U_\infty^2 c)$	
C_T	thrust coefficient; $-C_D$	
C_L	lift coefficient; $L/(0.5\rho U_\infty^2 c)$	
C_P	power coefficient; $LV_y/(0.5\rho U_\infty^3 c)$	

a power generation regime, the movement of the airfoil and the resultant force acting on the airfoil are in phase. This results in energy being transferred from the flowing fluid to the airfoil leading to power extraction. However, in a propulsion regime the movement of the airfoil and the resultant force acting on the airfoil are 180 degrees out of phase. This results in energy being transferred from the airfoil to the flowing fluid leading to propulsion. Heathcote et al. [9] studied the effect of spanwise flexibility on the thrust and propulsive performance of a rectangular wing that was oscillating in pure heaving motion. The results indicated that spanwise flexibility proved advantageous to a certain degree. It was observed that for a Strouhal number St > 0.2 a small degree of spanwise flexibility generated greater thrust and reduced power-input requirement thereby improved propulsive efficiency. However further increasing the degree of spanwise flexibility proved detrimental.

Katzmayr [15] was the first to perform experiments on a stationary airfoil that was placed in a sinusoidally oscillating wind stream and average thrust force generated was measured. The thrust generation due to sinusoidal oscillation of airfoil is known as Knoller–Betz effect [18,3]. Read et al. [25] experimentally investigated the effects of higher order heave motion on the thrust generation and propulsive efficiency of a NACA0012 airfoil undergoing combined plunging and pitching. It was found that a properly selected introduction of higher harmonics in the heave motion can reduce the angle of attack to a pure harmonic and increases substantially the thrust coefficient at high Strouhal numbers. Hover et al. [10] extended the study of Read et al. [25] to other non-sinusoidal motions: square wave, symmetric sawtooth wave and a cosine function. The experimental results demonstrated that the cosine profile achieves a significant improvement over other cases in terms of high thrust force with reasonable high efficiency. Viscous flow study around a symmetric airfoil was carried out by Lewin and Haj-Hariri [23] for a sinusoidal plunging airfoil. The study showed that wake patterns depend on vortex shedding from leading edge and their interaction with the trailing edge vortices. Numerical investigations were carried out for sinusoidal plunging airfoil by Young and Lai [29]. The study was conducted on a NACA0012 airfoil at a Reynolds number of 20000. The results showed that the wake structures, lift and thrust of the airfoil, were strongly dependent on both the Strouhal number and the reduced frequency $k$of the plunge oscillation at low Reynolds number. Most of these studies were focused on the airfoil in pure sinusoidal motion for studying the influence of various kinematic parameters. Kaya and Tuncer [16] studied the kinematics of flapping airfoil undergoing a combined, non-sinusoidal pitching and plunge motion. The results showed that the thrust generation can be significantly increased in comparison to the sinusoidal flapping motion. Lu et al. [24] conducted studies on a NACA0012 airfoil for both sinusoidal and non-sinusoidal pure pitching motion. The study was conducted for varying values of reduced frequency and pitch amplitude at Reynolds number 13500. It was observed that with an increase in reduced frequency and pitch amplitude, NACA0012 airfoil exhibited higher thrust for sinusoidal and non-sinusoidal pitch motion. Among sinusoidal and non-sinusoidal pitch motions, the latter showed better performance.

Cebeci et al. [4] used unsteady panel code simulations in comparison to Garrick's linear theory [8] for NACA0003, NACA0009, NACA0012 and NACA0015 airfoils. The studies showed a negligible effect of increasing thickness on the propulsive efficiency of a plunging airfoil. Rozhdestvensky and Ryzhov [26] briefly discussed the results of experiments conducted on an isolated rigid vertically submerged wing having NACA sections with thickness between 6% and 21% undergoing lateral oscillations in water at rest. In contrast to the inviscid calculations of Cebeci et al. [4], these results showed that the thrust increases with airfoil thickness. Lentink and Gerritsma [22] numerically studied the influence of airfoil shape with NS simulations on plunging airfoils at Reynolds number 150. The study involved the comparison between the performance between a NACA0010 section with a blunt 10% ellipse section and a thinner and sharper 2% ellipse NACA0002, NACA4702 airfoil sections. The study showed that the NACA0010 section created greater thrust than NACA0002 because of the higher frontal area.

Recently An et al. [1] used the Lattice Boltzmann method to study plunging bodies of varying thickness from 5% (thin ellipse), 10% and then in steps of 10–100% thick (circular cylinder) at very low Reynolds number of 50, 100, 185 and Strouhal number of 0.2 and 0.4. Based on the wake vortex pattern and velocity profiles behind the plunging body, thickness distribution of the airfoil was identified as a crucial design parameter for thrust generation. Ashraf et al. [2] systematically evaluated and quantified the effect of varying the thickness and camber on the propulsive performance of 2D NACA airfoils. The airfoils were subjected to pure plunging and pitching motions. It was observed that at low Reynolds numbers Re $= 200$, thin airfoils performed better than thick airfoils. At high Reynolds numbers thicker airfoils showed better performance when subjected to combined plunging and low amplitude pitching motion. Yu et al. [30] studied the effect of airfoil thickness and kinematic effects on airfoil propulsion. Studies were conducted for Strouhal number, St $= 0.45$ at Reynolds number, Re $= 1200$. The airfoils were subjected to pure sinusoidal plunging motions. The study showed that viscous force contributed to thrust generation in thin airfoils. Yu et al. [31] extended the above studies by subjecting the airfoil to combined sinusoidal pitching and plunging motions at low and high Strouhal numbers. It was observed that at low Strouhal numbers thin airfoils exhibited better efficiency but at high Strouhal numbers airfoils exhibited diverse trends for propulsive efficiency.

The conclusions that can be drawn from the literature study are that the studies carried out so far have been focused on either the effect of airfoil thickness or non-sinusoidal motion on propulsive performance. Airfoil propulsive performance was improved when subjected to non-sinusoidal pitching and/or plunging motion when

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