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Optimization of Propulsion in Flapping Micro Air Vehicles Using Genetic Algorithm Method

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***Abstract*—**In this paper the kinematic parameters of a regular Flapping Micro Air Vehicle (FMAV) is investigated. The optimization is done using multi-objective Genetic algorithm method. It is shown that the maximum propulsive efficiency is occurred on the Strouhal number of 0.2-0.3 and foil-pitch amplitude of 15°-30°. Furthermore, increasing pitch amplitude with respect to power optimization increases the thrust slightly until pitch amplitude around 30°, and then the trust is increased notably with increasing of pitch amplitude. Additionally, the maximum mean thrust coefficient is computed of 2.67 and propulsive efficiency for this value is 42%. Based on the thrust optimization, the maximum propulsive efficiency is acquired 54% while the mean thrust coefficient is 2.18 at the same propulsive efficiency. Consequently, the maximum propulsive efficiency is obtained 77% and the appropriate Strouhal number, pitch amplitude and phase difference between heaving and pitching are calculated of 0.27, 31° and 77°, respectively.

***Keywords*—**Flapping foil propulsion, Genetic algorithm, Micro Air Vehicle (MAV), Optimization.

I.INTRODUCTION

MICRO Air Vehicles (MAVs), which has dimension of less than 15 cm and flight speed around 10 m/s, operate at lower Reynolds number, based on the mean airfoil chord (almost lower than Re<150000) [1]. The success design of MAV requires contribution of different disciplines including aerospace and biology sciences. It is known that the flapping flight of birds is a coupled pitching and plunging oscillation with a phase difference between to these motions. This concept has led engineers to design the next generation of MAVs, which is named as Flapping Micro Air Vehicles (FMAVs). The FMAV mimics the birds to flight with simultaneously integrating lift, propulsion and control [2]. Fig. 1 shows schematic of a typical FMAV which is preliminary composed of a fixed body, two flapping wings and a controlled tail. The fixed body regularly consists of battery, flapping mechanism and motors, electrical controlling systems. Many experimental, theoretical and computational works have been performed for understanding of the flapping airfoil aerodynamics. It is still not clearly known how to distribute the pitching angle and plunging velocity over the flapping cycle to achieve a desired mean thrust and lift, at the same time minimize the power required to flap the wings at realistic frequencies and amplitudes [3].

In few recent decades, comprehensive researches have been done on the optimization of kinematic parameters of FMAV and its effect on aerodynamic forces to be involved in propulsion. Based on the observations from natures, Taylor et al. [4] observed that the Strouhal number is between 0.2 and 0.4. They also agreed on the pitching amplitude between 20° and 40°. The experimental and numerical analyses conducted by Triantafillou et al. [5] demonstrated that a Strouhal number between 0.2 and 0.4 causes the propulsive efficiency to be maximized. With respect to the numerical study by Pedro et al. [6] the appropriate pitch amplitude is also around 30°–40°. Additionally, Amiralaei et al. [7] performed the 2D Navier-Stokes which is associated with Finite Volume Method to model the flapping airfoil in low Reynolds Number flows. They showed that although Reynolds and Strouhal numbers have prominent influence on aerodynamic of flapping airfoil, the importance of pitch amplitude and phase angle difference between plunging and pitching is more than two remarked parameters. They also noted that the best aerodynamic performance is occurred in symmetrical oscillations. Furthermore, they demonstrated that increasing Reynolds number slightly increases the aerodynamic performance, but increasing relative heave amplitude does not have any noticeable effect on the propulsion performance.

The main goal of this study is optimization of kinematic parameters of flapping airfoil flight for FMAVs in order to have a flight operation with the minimal power consumption or fast flights. The optimization is done using the multi-objective genetic algorithms and according to the obtained results in the wide range of flight performance the best kinematic parameters are determined.

Fig. 1 Schematic of a typical FMAV which mimics the birds to flight

II. PHYSICAL MODEL

In this section the kinematics of flapping airfoil and some concepts are briefly explained. In Fig. 2 the airfoil is placed in

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opposed direction of free stream velocity, U. The distance between leading edge (LE) and trailing edge (TE) is chord, c, and AC indicates the aerodynamic center of foil, at which the foil velocity acts on that point. The angle between chord line and free stream velocity is pitch angle and is indicated as θ. Additionally, x_o and x_i are location of pitch axis (PA) and incident velocity with respect to leading edge (LE), respectively. Furthermore, M and $\dot{h}$ are pitching moment and derivative of heaving, respectively.

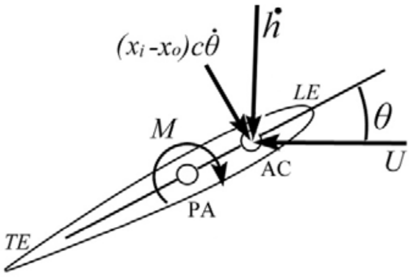

Fig. 2 Schematic of flapping airfoil and related velocities acting on it

In design purpose, the heave and pitch motions for flapping flight are considered as harmonic sinusoidal functions with constant frequency, f. Thus, they are defined as:

$$h(t) = h_0 \sin(\omega t) \tag{1}$$

$$\theta(t) = \theta_0 \sin(\omega t + \psi) \tag{2}$$

where, ω and ψ are angular velocity ($\omega = 2\pi f$) and phase angle difference between heaving and pitching, respectively.

With definition of foil velocity, the velocity components which are parallel and normal to direction of chord line can be defined, respectively, as follows:

$$V_p = U\cos\theta - \dot{h}\sin\theta \tag{3}$$

$$V_n = U\sin\theta + \dot{h}\cos\theta + (x_i - x_o)c\dot{\theta} \tag{4}$$

The last term of (4) is pitch velocity due to rotation of foil around pitch axis (PA). Consequently, the incident velocity magnitude can be defined as:

$$|V|^2 = {V_p}^2 + {V_n}^2 \tag{5}$$

The angle of attack is angle between incident velocity and chord line. The incident velocity is varied along the chord line due to pitch velocity. Thus, the overall angle of attack can be defined as:

$$\alpha = tan^{-1}(V_n/V_p) \tag{6}$$

In kinematics of flapping airfoil the essential parameter is effective angle of attack because it affects directly on aerodynamic performance of flapping and, of course, on propulsion.

III. Aerodynamic Model

The present aerodynamic model follows a 2D quasi-steady approximation which follows Theodorsen theory [8]. Some aspects are originated from aerodynamic model for flapping-wing flight [9]. According to aerodynamic of lift body, the lift force due to flapping airfoil can be defined as:

$$L = \frac{1}{2}\rho\pi c \sin\left(2\alpha|_{x_i=\frac{3}{4}}\right) C(k) \left(V|_{x_i=\frac{1}{4}}\right)^2 + \frac{1}{4}\rho\pi c^2 \left(\dot{V_n}|_{x_i=\frac{1}{2}}\right) \tag{7}$$

where, k represents reduced frequency ($k = \pi f c/U$) and $C(k)$ is a complex function and is defined as:

$$C(k) = \frac{H_1^{(2)}(k)}{H_1^{(2)}(k) + iH_0^{(2)}(k)} \tag{8}$$

where, $H_j^{(2)}$are Hankel function [10] and can be expressed in terms of Bessel functions of first and second kind, $H_j^{(2)} = J_j - iY_j$. The total drag due to skin friction and pressure gradient of airfoil can be written as follows:

$$D = \frac{1}{2}\rho c \left(C_{df}{V_p}^2 + C_{dp}\left(V_n|_{x_i=\frac{1}{4}}\right)^2\right)^{0.5} \tag{9}$$

where, C_{df} and C_{dp} are drag coefficients at α=0° and α=90°, respectively. The maximum drag coefficient of NACA0012 airfoil at α=90° and Re=5.3×10^3-1.05×10^4 are reported 1.66-1.96 [11]. The friction coefficient can be accounted by empirical relations presented in [12].

IV. Propulsion model

The force components in x and y directions are written as follows:

$$F_x = L\sin\left(\theta + \alpha|_{x_i=\frac{1}{4}}\right) - D\cos\left(\theta + \alpha|_{x_i=\frac{1}{4}}\right) \tag{10}$$

$$F_y = L\cos\left(\theta + \alpha|_{x_i=\frac{1}{4}}\right) + D\sin\left(\theta + \alpha|_{x_i=\frac{1}{4}}\right) \tag{11}$$

The parameter that can implies the generated thrust force by oscillating foil is mean thrust coefficient and is defined as follows:

$$C_T = \frac{\frac{1}{T}\int_0^T F_x(t)dt}{\frac{1}{2}\rho A_f U^2} \tag{12}$$

where, $F_x(t)$ is instantaneous force in propulsion direction, T represents duration on one cycle and A_f is surface area of airfoil. The input power is also defined as:

$$P = \frac{1}{T}\int_0^T (F_y(t)\,\dot{h} + M(t)\dot{\theta})dt \tag{13}$$

where $F_y(t)$ is instantaneous loss force. Additionally, $\dot{\theta}$ is defined as derivative of pitch motion. The power coefficient is defined as:

$$C_P = \frac{P}{\frac{1}{2}\rho A_f U^3} \tag{14}$$

The overall propulsive efficiency is defined as ratio of trust coefficient to power coefficient and can be expressed by:

$$\eta = \frac{C_T}{C_P} \tag{15}$$

V. VALIDATION STUDY

The validation is done based on the instantaneous lift and thrust of flapping airfoil during one oscillation period. Lian and Shyy [1] used Navier-Stokes solver to study the aerodynamics of flapping airfoil. The Strouhal number, reduced frequency and phase angle difference between pitching and plunging were 0.3, 0.63 and 75°,repectively and the nominal angle of attack was α_0=15°. Fig. 3 (a) presents the instantaneous lift coefficient during one oscillation period. The produced lift profile is in agreement with that of computational results. In Fig. 3 (b) the present calculated thrust is also in agreement with computational results, but the negative thrust is over estimated when the foil is changed its plunge direction.

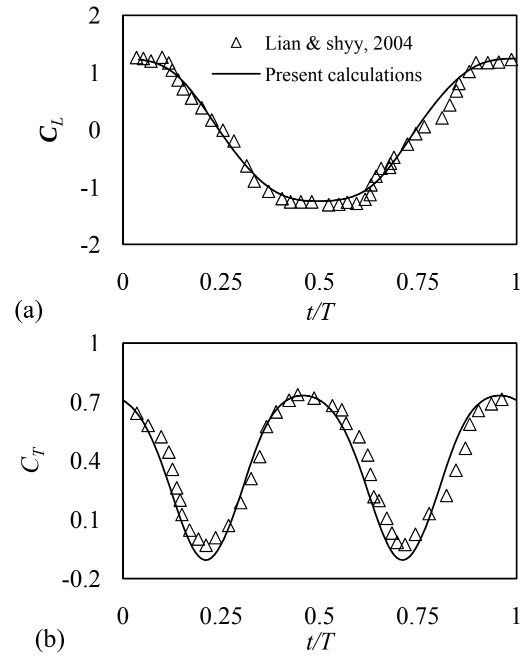

Fig. 3 Comparison of instantaneous lift and thrust coefficients of flapping foil for present calculations and computational results of Lian and Shyy [1]

VI. RESULTS AND DISCUSSION

The parameters considered in this simulation are provided in Table I. The unit and value (or values) of each given parameter are specified. Free stream velocity, air density, chord length and heave amplitude are kept in constant values, while the Strouhal number, foil-pitch amplitude and phase angle between heaving and pitching are manipulated.

TABLE I
UNIT AND VALUE (OR VALUES) OF GIVEN PARAMETERS FOR SIMULATION OF FLAPPING FOIL PROPULSION

Parameter	Unit	Values
U	[m/s]	0.5
ρ	[kg/m^3]	1.225
h_0/c	[-]	1
ψ	[degree]	90
θ_0	[degree]	10-50
$St = 2h_0 f/U_0$	[-]	0.1-0.6
c	[m]	0.1

Based on the two unknown parameters are specified (Strouhal number and foil-pitch amplitude), and the genetic algorithm is used to manipulate these two parameters for determining of the best options. According to the maximum propulsive efficiency the best options for the two unknown parameters are computed. For thorough considerations, the variations of propulsive efficiency with foil-pitch amplitude, θ_0, are plotted in Fig. 4. As it is shown, increasing pitch amplitude causes the propulsive efficiency to be increased until θ_0=25°, and after that increasing pitch amplitude leads the propulsive efficiency to be subsided. The maximum optimized propulsive efficiency is predicted 74% at θ_0=25°. In this pitch amplitude, the mean thrust coefficient is also calculated as 0.24.

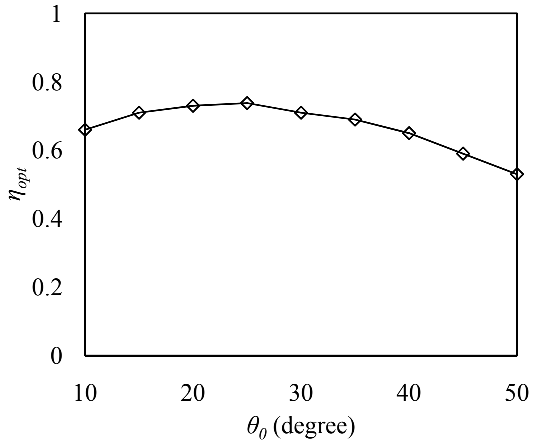

Fig. 4 The variations of optimized propulsive efficiency with foil-pitch amplitude

In Fig. 5 increasing pitch amplitude increases the mean thrust coefficient. The mean thrust coefficient is moderately increased until θ_0=30°. Subsequently, it increases notably between θ_0=30° and 45°.

The manipulated Strouhal number which leads to maximum propulsive efficiency is shown in Fig. 6. At lower pitch amplitudes the Strouhal number is kept on lower values. Additionally, at higher pitch amplitudes, the magnitude of manipulated Strouhal number is also at higher ones. Thus it is concluded that with increase in the value of pitch amplitude the manipulated Strouhal number is also increased. According to previous statements regarding flapping foil optimization, the pitch and Strouhal number, at which the propulsive efficiency is maximum, are reported θ_0=20°-30° and St=0.2-0.25, respectively.

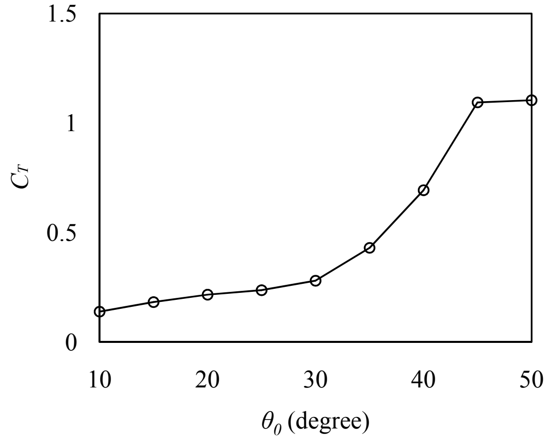

Fig. 5 Variations of the mean thrust coefficient with foil-pitch amplitude based on the maximum propulsive efficiency

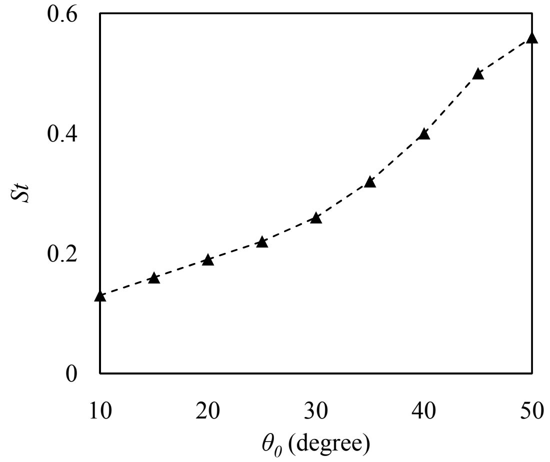

Fig. 6 Variations of Strouhal number with foil-pitch amplitude based on the maximum propulsive efficiency

Based on the maximum thrust, the foil-pitch amplitude and Strouhal number is simultaneously manipulated using genetic algorithm and it is shown in Fig. 7. As it is presented the maximum mean thrust coefficient is increased as pitch amplitude increases until θ_0=25°, and then it is decreased with increasing of the pitch amplitude. The maximum mean thrust coefficient can be obtained is up to 2.5 and this value is achievable at foil-pitch amplitude of 20°-30° and the maximum considered Strouhal number (St=0.6).

The related propulsive efficiency which is calculated with respect to the maximum mean thrust coefficient is plotted in Fig. 8. As seen from Fig. 8, the propulsive efficiency is enhanced as pitch amplitude is increased until θ_0=45°, and then it is dropped for further pitch amplitudes. Furthermore, the maximum propulsive efficiency, based on the optimization of the thrust, is 53% at pitch amplitude of 45°.

Consequently, to acquire the maximum propulsive efficiency the optimization is considered with three manipulated parameters, including on Strouhal number, pitch amplitude and phase difference between heaving and pitching. The conclusion can be drawn is that the maximum propulsive efficiency can be obtained in flapping foil propulsion is 77% and the manipulated Strouhal number, pitch amplitude and phase difference between heaving and pitching are 0.27, 31° and 77°, respectively.

Optimization of flapping foil propulsion based on propulsive efficiency or thrust produced by contribution of oscillations is applicable for different purpose. Improvement of propulsive efficiency can be effective in long time flights and high thrust may be used for escape or high loaded bodies. Thus, according to different flight conditions the kinematic parameters can be manipulated to approach the best performance in steady flights.

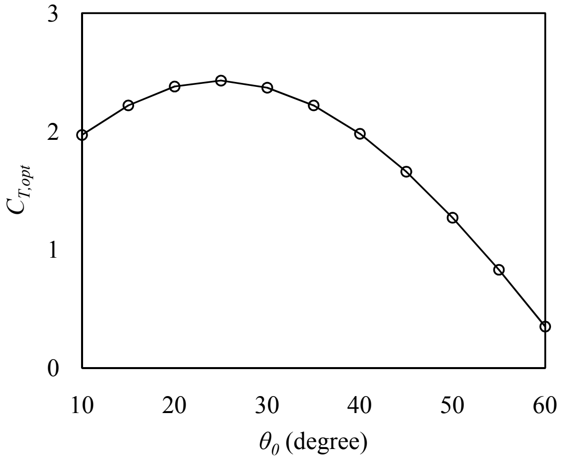

Fig. 7 Changes of the optimized thrust coefficient with foil-pitch amplitude

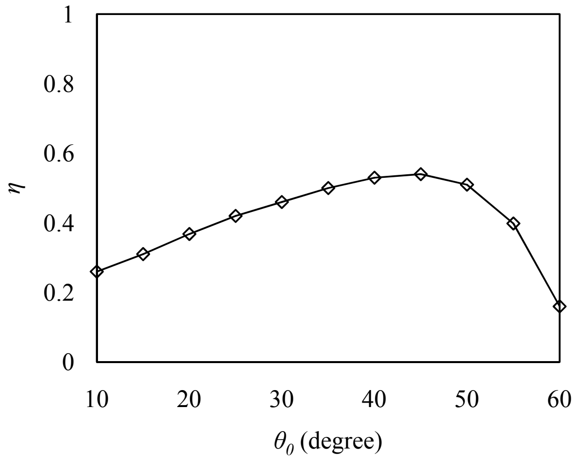

Fig. 8 Changes of the propulsive efficiency with foil-pitch amplitude based on the maximum mean thrust coefficient

VII.CONCLUSION

In this paper the optimization of flapping foil propulsion is done with respect to flight kinematics. A rectangular NACA0012 airfoil with high aspect ratio is specified and according to manipulation of two essential kinematic parameters the optimization is done. The optimization procedure is done based on the both propulsive efficiency and thrust. The aerodynamic model used for simulation of flapping foil follows 2D quasi-steady approximation. It is shown that the maximum propulsive efficiency can be obtained in Strouhal number of 0.2-0.3 and pitch amplitude of 15°-30°. Additionally, the maximum mean thrust coefficient is computed of 2.67 and propulsive efficiency for this value is 42%. Based on the thrust optimization, the maximum propulsive efficiency is reported 54% while the mean thrust coefficient is 2.18 at the same propulsive efficiency. It should be mentioned that the maximum propulsive efficiency based on the power consumption and thrust is occurred in moderate pitch amplitudes (20°-30°) and higher pitch amplitudes (40°-50°), respectively. Finally, the maximum propulsive efficiency may be approach to 77% and the appropriate Strouhal number, pitch amplitude and phase difference between heaving and pitching are obtained 0.27, 31° and 77°, respectively.

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