Optimization of flapping-wing micro aircrafts based on the kinematic parameters using genetic algorithm method

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Abstract: *In this paper the optimization of kinematics, which has great influence in performance of flapping foil propulsion, is investigated. The purpose of optimization is to design a flapping-wing micro aircraft with appropriate kinematics and aerodynamics features, making the micro aircraft suitable for transportation over large distance with minimum energy consumption. On the point of optimal design, the pitch amplitude, wing reduced frequency and phase difference between plunging and pitching are considered as given parameters and consumed energy, generated thrust by wings and lost power are computed using the 2D quasi-steady aerodynamic model and multi-objective genetic algorithm. Based on the thrust optimization, the increase in pitch amplitude reduces the power consumption. In this case the lost power increases and the maximum thrust coefficient is computed of 2.43. Based on the power optimization, the results show that the increase in pitch amplitude leads to power consumption increase. Additionally, the minimum lost power obtained in this case is 23% at pitch amplitude of 25°, wing reduced frequency of 0.42 and phase angle difference between plunging and pitching of 77°. Furthermore, the wing reduced frequency can be estimated using regression with respect to pitch amplitude, because reduced frequency variations with pitch amplitude is approximately a linear function.*

Key Words: *Flapping-wing micro aircraft, Aerodynamics, Flapping foil propulsion, optimization, genetic algorithm.*

1. INTRODUCTION

The micro aircrafts are designed based on the tree ways for lift generations. They are fixed, rotary and flapping wings. Among of these methods the flapping wing propulsion systems occupy a special place because so many living species have developed them [1]. For comparison of man-made objective and flying creatures, researchers use the relative speed parameter. (ratio of the speed of flying to maximum length of an object). The birds and insects have relative speed between 60 and 170, while this value for jet airplanes is between 4 and 9 [2]. These notes demonstrate the importance of flapping crafts to design of more efficient airplanes to reach to higher relative speeds.

A successful design of flapping-wing crafts requires the contribution of different disciplines including aerospace and biology. It is known that flapping flight of birds is a coupled pitching and plunging oscillation with a phase difference between these two motions. This concept has led engineers to design the next generation of flapping-wing crafts. Figure 1 shows a schematic of a typical flapping-wing craft which is preliminary composed of a fixed body, two flapping-wings and a controlled tail. The fixed body typically consists of battery, flapping mechanism and motors, electrical controlling systems.

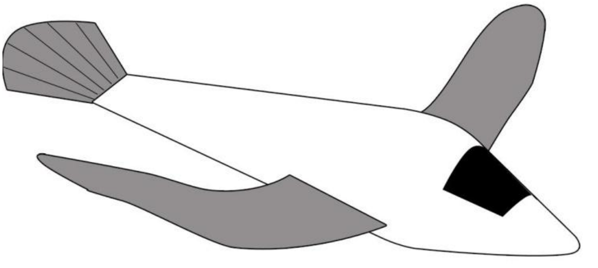

Fig. 1 – Schematic of a typical flapping-wing micro aircraft which imitates the birds in flight

Many experimental, theoretical and computational works have been conducted for understanding the flapping-wing 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 and at the same time to minimize the required power for flapping the wings at realistic frequencies and amplitudes [3].

In the last few years, comprehensive researches have been conducted on the kinematic optimization of flapping-wing vehicles and on its influence on aerodynamics involved in propulsion. The experimental and numerical analyses conducted by Triantafyllou et al. [4] showed that a Strouhal number between 0.2 and 0.4 leads the propulsive efficiency to be maximized. With respect to the numerical study by Pedro et al. [5] the appropriate pitch amplitude is also around 30°–40°. Based on the observations from natures, observations by Taylor et al. [6] demonstrate the obtained results by experimental and computational works. For more descriptions, Amiralaei et al. [7] developed the 2D Navier-Stokes which is associated with Finite Volume Method simulating the flapping-wing in low Reynolds Number flows. They have demonstrated that the importance of pitch amplitude and phase angle difference between plunging and pitching is more than Reynolds and Strouhal numbers. They also announced that the best aerodynamic performance occurs in symmetrical oscillations.

The main goal of this work is optimizing the kinematic parameters of flapping-wing flight for design of the efficient flapping-wing crafts in order to have a flight operation with the minimal power consumption or fast flights. The optimization is conducted using the multi-objective genetic algorithm to determine the appropriate ranges of kinematic parameters at which the propulsion performance is the best selections.

2. PHYSICAL MODEL

In this section the flapping-wing kinematics and some concepts are briefly described. Figure 2(a) displays the pattern of wing motion. The wing flaps up and down with harmonic changes in pitch motion. The amplitude of plunge motion is defined as plunge amplitude and can be written as h_0.

In Figure 2 (b), the wing is placed in 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 wing, at which the wing velocity acts on that point. The angle between chord line and free stream velocity is the pitch angle and is defined as θ. Furthermore, x_o and x_i are location of pitch axis (PA) and incident velocity with respect to leading edge (LE), respectively. Additionally, $\dot{h}$ and M are pitching moment and derivative of plunging, respectively.

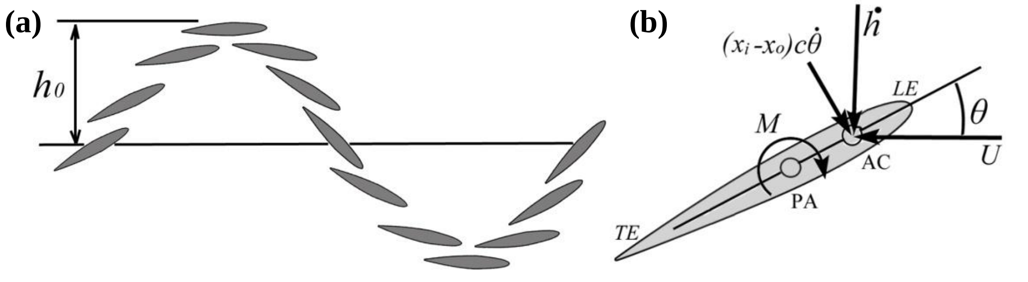

Fig. 2 – Schematic of flapping-wing motion and related velocities acting on wing

The plunge and pitch motion for flapping-wing flight are considered as harmonic sinusoidal function 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 plunging and pitching, respectively. The incident velocity magnitude can be defined as:

$$|V|^2 = \left(U\cos\theta - \dot{h}\sin\theta\right)^2 + \left(U\sin\theta + \dot{h}\cos\theta + (x_i - x_0)c\dot{\theta}\right)^2 \tag{3}$$

The effective angle of attack is the angle between incident velocity and chord line. The incident velocity is varied through the chord line because of some variations in pitch velocity.

Thus, the overall effective angle of attack can be written as follows:

$$\alpha = \tan^{-1}\left[\frac{U\sin\theta + \dot{h}\cos\theta + (x_i - x_0)c\dot{\theta}}{U\cos\theta - \dot{h}\sin\theta}\right] \tag{4}$$

In the present simulation the independent parameters which are considered on the flapping-wing aerodynamics are Reynolds number ($\mathrm{Re} = \rho Uc/\mu$), reduced frequency ($k = \pi fc/U$) and relative plunge amplitude ($h^* = h_0/c$).

The considered airfoil for wing design is a rigid NACA0012. The pitch-axis (PA) and the aerodynamic center of this airfoil are located at 1/3 and 1/4 of the chord length.

3. AERODYNAMIC MODEL

The present aerodynamic model follows a 2D quasi-steady approximation which follows Theodorsen theory [8]. Some definitions and features 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:

$$L = \frac{1}{2}\rho\pi c C(k)\sin\left(2\alpha|_{x_i=\frac{3}{4}}\right)\left[V|_{x_i=\frac{1}{4}}\right]^2 + \frac{1}{4}\rho U\dot{\theta}\pi c^2\cos\theta + \frac{1}{4}\rho\pi c^2\ddot{h}\cos\theta + \frac{1}{4}\rho\pi\dot{h}\dot{\theta}c^2\sin\theta + \frac{1}{4}\rho\pi c^3\left(\left(\frac{1}{2}-x_0\right)\ddot{\theta}\right) \tag{5}$$

Where $C(k)$ is a complex function and is defined as:

$$C(k) = \frac{H_1^{(2)}(k)}{H_1^{(2)}(k) + iH_0^{(2)}(k)} \tag{6}$$

where, $H_{0,1}^{(2)}(k)$ is Hankel function [10] and can be expressed in terms of Bessel functions of first and second kind, $H_1^{(2)}(k) = J_j - iY_j$. The total drag due to skin friction and pressure gradient of airfoil can be written as follows:

$$D = \frac{1}{2}\rho c\left[C_{DF}\left(U\cos\theta - \dot{h}\sin\theta\right)^2 + C_{DP}\left(U\sin\theta + \dot{h}\cos\theta + \left(\frac{1}{4}-x_0\right)c\dot{\theta}\right)^2\right]^{0.5} \tag{7}$$

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 $Re=5.3\times10^3-1.05\times10^4$ are reported 1.66-1.96 [11].

4. PROPULSION MODEL

The force components in *x* and *y* directions are defined as F_x and F_y, respectively and can be written as follows:

$$F_x = L\sin\left(\theta + \alpha|_{x_i=\frac{1}{4}}\right) - D\cos\left(\theta + \alpha|_{x_i=\frac{1}{4}}\right) \tag{8}$$

$$F_x = L\cos\left(\theta + \alpha|_{x_i=\frac{1}{4}}\right) + D\sin\left(\theta + \alpha|_{x_i=\frac{1}{4}}\right) \tag{9}$$

The generated thrust force by flapping-wing is named as mean thrust coefficient and is defined as follows:

$$C_T = \frac{\frac{1}{T}\int_0^T F_x(t)dt}{\frac{1}{2}\rho c U^2} \tag{10}$$

where, F_x is instantaneous force in propulsion direction, *T* represents duration on one cycle. The input power is also defined as:

$$P = \frac{1}{T}\int_0^T F_y(t)\dot{h}dt + \frac{1}{T}\int_0^T M(t)\dot{\theta}dt \tag{11}$$

The power coefficient is defined as:

$$C_P = \frac{P}{\frac{1}{2}\rho c U^3} \tag{12}$$

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

$$\eta = C_T / C_P \tag{13}$$

5. OPTIMAZATION METHOD

Some of significant characteristics of optimization algorithms are generality of formulation, robustness, capability of handling multi-objectives and computational efficiency. In this study the genetic algorithm is utilized to figure out the minimum lost power and thrust coefficient as output, for each various input independent parameters. The lost power can help to realize the propulsive efficiency and according to gained results, the best options for maximum propulsive efficiency are determined. The genetic algorithm is based on Darwin's evolution theory, at which a randomly generated population is used as initial population. In this model, the numbers of populations and the maximum generations are 100 and 150, respectively.

6. VALIDATION STUDY

The validation is based on the instantaneous lift and thrust of flapping airfoil. Lian and Shyy [3] used Navier-Stokes solver to study the aerodynamics of flapping airfoil. The reduced frequency is 0.63, the phase angle difference between pitching and plunging is 75°, and the nominal angle of attack is α_0=15°. Figure 3(a) displays the instantaneous lift coefficient during one oscillation period. The lift profile coincides with that of computational results. In Figure 3(b) the present calculated thrust is also in agreement with computational results.

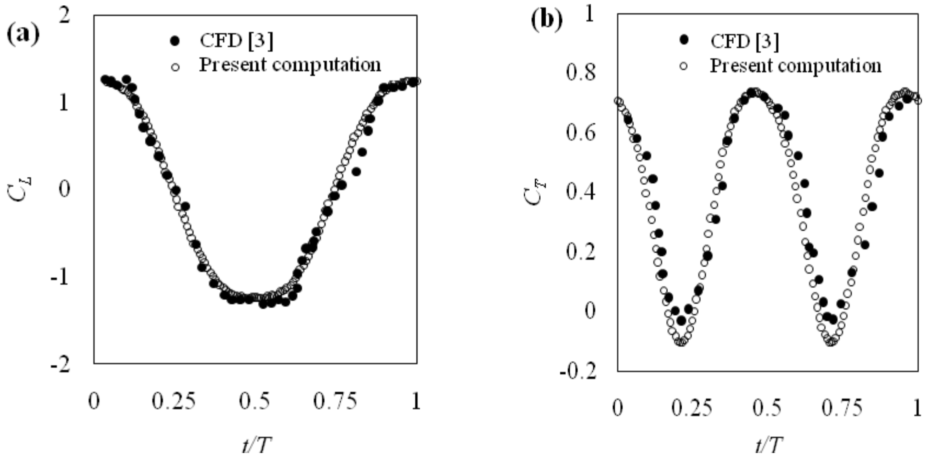

Fig. 3 – Comparison of instantaneous lift and thrust coefficients of flapping foil for present calculations and computational results [3]

7. RESULTS AND DISSCUSION

The parameters considered in this simulation are provided in Table 1. The unit and value (or values) of each given parameter are specified. Free stream velocity, air density, chord length and plunge amplitude are kept in constant values, while the Strouhal number, foil-pitch amplitude and phase angle between plunging and pitching are manipulated.

Table 1 – Values of given parameters for simulation of flapping foil propulsion

given parameter	values
U	0.6 m/s
ρ	1.225 kg/m^3
h^*	1
ψ	70°-110°
θ_0	10°-50°
k	0.1-0.6
c	0.1 m

Based on the two unknown specified parameters (Strouhal number and foil-pitch amplitude), the genetic algorithm is used to manipulate these two parameters for determining the best options. According to the maximum propulsive efficiency the best options for the two unknown parameters is taken into account. Figure 4 displays the mean power and thrust coefficients variations with pitch amplitude. The increasing pitch amplitude increases the mean power coefficient slightly until θ_0=30°, and then the mean power coefficient raises considerably with pitch amplitude increasing. Furthermore, higher pitch amplitude enhances the mean thrust coefficient. The mean thrust coefficient is slightly increased until θ_0=30°. Subsequently, it increases notably between θ_0=30° and 45°. Thrust coefficient is always lower than the mean power coefficient and their gradient values represent the performance efficiency. As it is shown, the gradient value increases notably after θ_0=30° and this action shows the performance efficiency would be decreased with pitch amplitude increasing.

For thorough considerations, the variations of lost power with foil-pitch amplitude are depicted in Figure 5. As it is shown, increasing pitch amplitude causes the power loss to be decreased until θ_0=25°, and after that increasing pitch amplitude provides the lost power to be enhanced. The minimum lost power is predicted 26% at θ_0=25°.

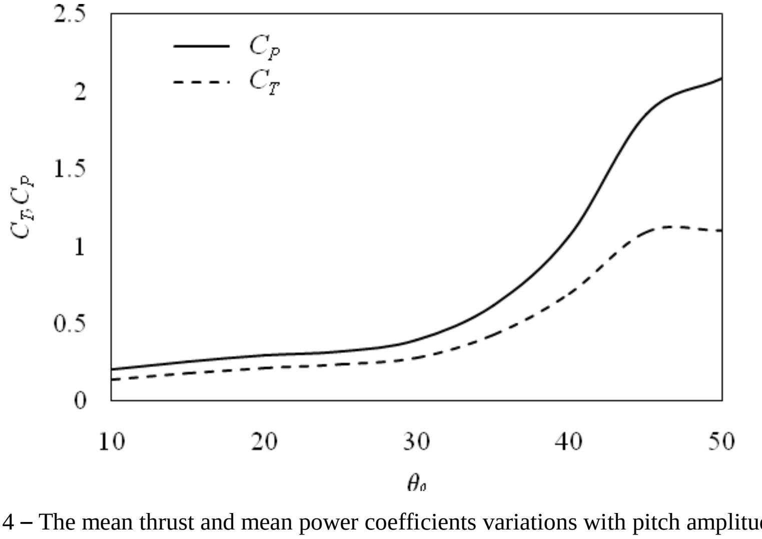

Fig. 4 – The mean thrust and mean power coefficients variations with pitch amplitude

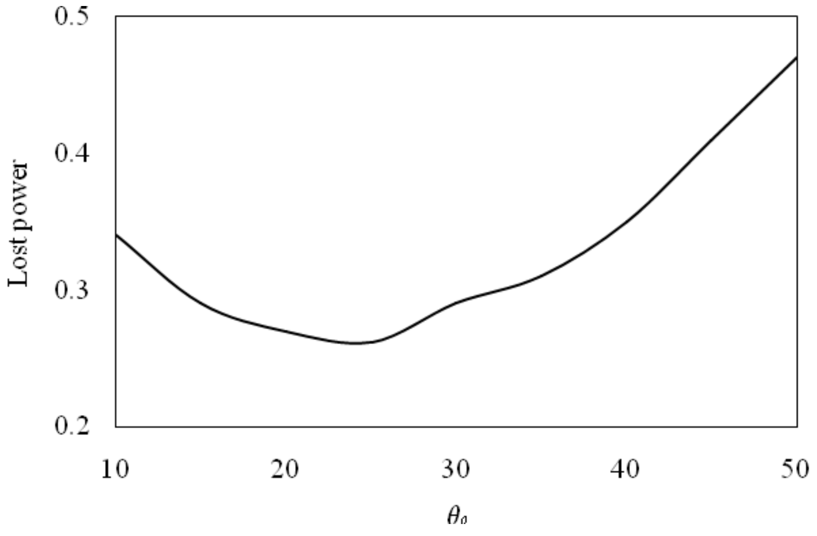

Fig. 5 – The minimum lost power changes in different pitch amplitude

Figure 6 represents the maximum propulsive efficiency in different pitch amplitudes. As it is shown, with pitch amplitude increasing the propulsive efficiency increases until θ_0=25° and then, as pitch amplitude increases the propulsive efficiency subsides to lower values. The minimum and maximum optimized propulsive efficiency are predicted 53% at θ_0=50° and 74% at θ_0=25°.

In this pitch amplitude, the mean thrust coefficient is also calculated as 0.24.

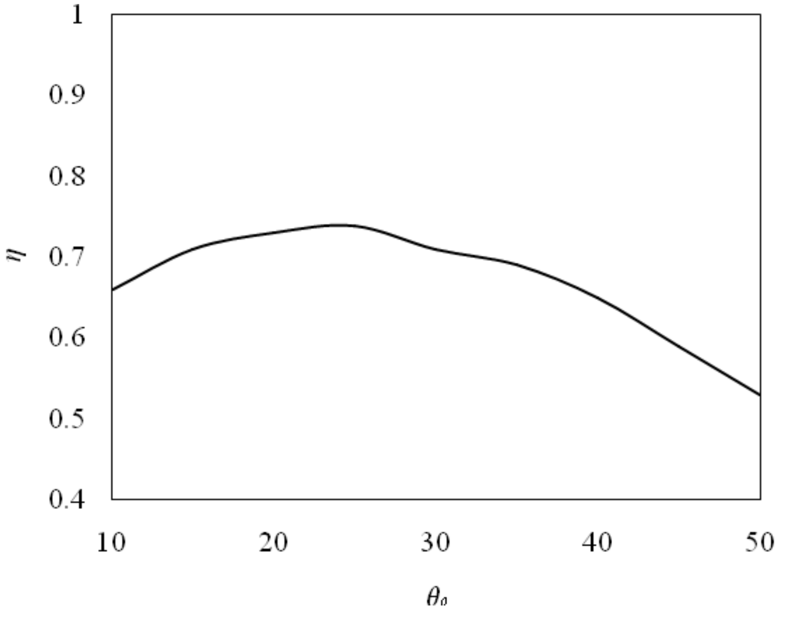

Fig. 6 – The variations of optimized propulsive efficiency with foil-pitch amplitude

Figure 7 shows the manipulated reduced frequency which leads to maximum propulsive efficiency. At pitch amplitude of 10° the reduced frequency is around 0.2. Additionally, as pitch amplitude increase the manipulated reduced frequency is also increased approximately with a linear function.

According to previous statements regarding flapping-wing optimization, the reduced frequency, at which the propulsive efficiency would be maximum, is of 0.34.

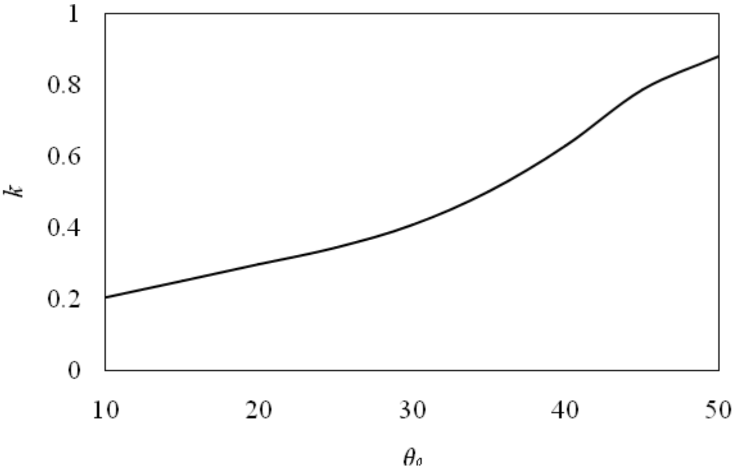

Fig. 7 – The variations of reduced frequency with pitch amplitude based on the maximum propulsive efficiency

Based on the maximum thrust, the reduced frequency and pitch amplitude are simultaneously manipulated and the best options for maximum thrust are found. Figure 8 shows the maximum mean thrust coefficient and related mean power coefficient in different pitch amplitudes.

The maximum mean thrust coefficient is increased as pitch amplitude increases until θ_0=25°, and then it is decreased with pitch amplitude increasing. The maximum mean thrust coefficient is accounted up to 2.43 and this value is achievable at foil-pitch amplitude of 20°-30° and the maximum considered reduced frequency.

The related mean power coefficient is also calculated with respect to the maximum mean thrust coefficient.

As seen in Figure 0, the mean power coefficient decreases as pitch amplitude is increased until θ_0=55°, and then it is slightly increased. It is concluded that at lower pitch amplitudes the required power is higher than that at higher pitch amplitudes.

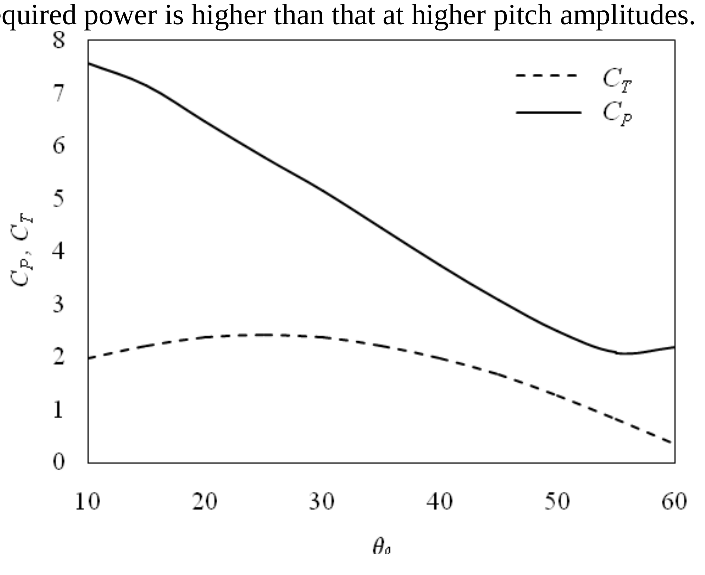

Fig. 8 – Changes of the optimized thrust coefficient with foil-pitch amplitude

Finally, to achieve the maximum propulsive efficiency the optimization is considered with three manipulated parameters, including reduced frequency, pitch amplitude and phase difference between plunging and pitching.

The conclusion that can be drawn is that the maximum propulsive efficiency that can be earned is of 77% and the manipulated reduced frequency, pitch amplitude and phase difference between plunging and pitching are 0.42, 31° and 76°, respectively.

Optimization of flapping-wing micro aircrafts based on propulsive efficiency or thrust can be used to design and manufacture more efficient crafts with sufficient speed.

These types of micro aircraft can cross the oceans with minimal power consumption and pose a new kind of craft ages in near future.

8. CONCLUSION

In this paper the optimization of flapping-wing micro aircraft based on the kinematics of flying is conducted using the multi-objective genetic algorithm.

A rectangular NACA0012 airfoil with high aspect ratio is specified and according to manipulation of pitch amplitude, wing reduced frequency and phase difference between plunging and pitching the optimization is done.

The optimization procedure is performed based on the both propulsive efficiency and thrust. The aerodynamic model used for simulation of flapping foil follows 2D quasi-steady approximation.

It is demonstrated that the maximum propulsive efficiency can be obtained at wing reduced frequency of 0.31-0.47 and pitch amplitude of 20°-30°. In this case the minimum power loss is 26%, while the maximum propulsion efficiency can reach 74%.

Additionally, the maximum mean thrust coefficient is accounted for 2.43. At lower pitch amplitude the power consumption to earn maximum thrust is relatively higher than power required achieving maximum propulsive efficiency.

Furthermore, with increase in pitch amplitude, the power consumption would be increased in power optimization case, while this value would be decreased in thrust optimization case. Finally, the maximum propulsive efficiency may be obtained during flapping foil propulsion is accounted for 77% and the appropriate reduced frequency, pitch amplitude and phase difference between plunging and pitching are obtained 0.42, 31° and 77°, respectively.

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