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COMPARATIVE INVESTIGATIONS IN THE EFFECT OF ANGLE OF ATTACK PROFILE ON HYDRODYNAMIC PERFORMANCE OF BIO-INSPIRED FOIL

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Abstract:

In flapping underwater vehicles the propulsive performance of harmonically sinusoidal heaving and pitching foil will be degraded by some awkward changes in effective angle of attack profile, as the Strouhal number increases. This paper surveys different angle of attack profiles (Sinusoidal, Square, Sawtooth and Cosine) and considers their thrust production ability. In the wide range of Strouhal numbers, thrust production of Square profile is considerable but it has a discontinuity in heave velocity profile, in which an infinite acceleration exists. This problem poses a significant defect in control of flapping foil. A novel profile function is proposed to omit sharp changes in heave velocity and acceleration. Furthermore, an optimum profile is found for different Strouhal numbers with respect to Square angle of attack profile.

Keywords: Hydrodynamics, bio-inspired foil, underwater vehicle, angle of attack profile, Strouhal number.

NOMENCLATURE

A	wake width $2h_o$
c	chord length
C_L	lift coefficient,
C_P	power coefficient
C_T	thrust coefficient
f	flapping frequency
$F_x(t)$	thrust force
$F_y(t)$	loss force
h_o	amplitude of nominally sinusoidal heave motion h(t)
$M_o(t)$	Torque
$P(t)$	mechanical power supplied by actuators
Re	Reynolds number, Re=Uc/ν
s	Foil span
St	Strouhal numbers, St=$2fA/U$
U	foil velocity
Greek symbols	
α_{max}	maximum of angle of attack $\alpha(t)$
β	slope factor
θ_o	amplitude of sinusoidal pitch motion $\theta(t)$
ν	fluid kinematic viscosity
ρ	fluid density
φ	angle of heave velocity
ω	Angular velocity, $\omega=2\pi f$
ψ	phase angle of pitch motion

1. Introduction

The birds and fishes are astoundingly best flyer and swimmers. The idea of using oscillating wings as propulsors, originates in the observation of the flying and swimming capabilities of these animals. The basic source of locomotion and maneuvering force is oscillating foil, which can undergo simultaneous translation and rotation in two or more degree of freedom. The foils generate a large scale vortex wakes, which associated with both drag force and thrust. The drag wake is analogous to von Karman street behind a bluff body and its direction is parallel to flow stream. Thus, most fish and cetaceans move around their aquatic environment by flapping their tail (foil shaped tail). The high level of efficiency of flapping foils, along with their other useful properties such as their low-noise characteristics and maneuverability. Furthermore, control of unsteady vortex creates very high lift coefficient (Gursul and Ho, 1992) and oscillating foil provides efficient propulsion for underwater locomotion (Anderson et al., 1998; Triantafyllou et al., 1993). An oscillating foil can also be used to manipulate incoming vorticity, and recapture vertical energy (Cortelezzi et al., 1997; Gopalkrishnan et al., 1994; Streitlien et al., 1996). Furthermore, Esfahani et al. (2.13) found that the caudal in fish-like swimming could improve the propulsive efficiency, which it introduces the fish-like swimming more efficient than flapping-wing

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flying. Underwater locomotion is a subject that attracts attentions of many scientists and it causes to be done vast research on performance and maneuverability of vehicles with this mechanism (Bandyopadhyay et al., 1997; Kato, 1998). In underwater vehicles, the disadvantage of flapping foil to be used as propulsors is that the foil generates side force beside thrust and this effect cause vehicle to have deviation from motion axis and it is essential to equalize and control this useless torque with contrast torque that has same magnitude.

Dynamic properties of foil and wake are essential for complete characterization and flow visualization. Large angle of attack due to pitch or heave results in strong leading edge separation, which weakens the thrust. Furthermore, reducing the frequency of oscillation causes the vortex roll-up of the wake to become more and more sluggish until usual von Karman Street and associated drag profile become evident. Anderson et al. (1998) and Koochesfahani (1989) performed experiments on various types of foil in order to consideration of flapping foil performance. They observed that for heaving foil with specified parameters, a thrust-type vortex street is formed by a weak leading edge separation, which travels down the foil and constructively merges with the trailing edge vortex. Anderson (1996) performed Digital Particle Image Velocimetry (DPIV) on a foil oscillating in both pitch and heave, and found that at least six distinct vortex formation regimes exist for the range of parameters, but a region of optimal wake formation, characterized by two vortices per cycle in a reverse von Karman pattern, occupies St=0.2-0.5 and α_{max}=7º-50º. Hover et al. (2004) in their experimental investigations demonstrated that in most cases the high efficiencies for flapping foil propulsion occurred in low Strouhal numbers and, of course, in low thrust coefficients. On the other hand, high thrust coefficients limited in low efficiencies. Esfahani et al. (2013) also demonstrated the mentioned results for flapping flight, with multi objective optimization of flapping airfoil propulsion using genetic algorithm. Detailed experimental analysis related to the effects of kinematics as well as the wake visualization behind the flapping airfoils can be found in recent works by Read et al. (2003) and Schouveiler et al. (2005).

The objective of this paper is investigations on high speed flapping foil propulsion. The main requirement of this approach is high thrust force in order to cover all resistances being appeared during locomotion. In present work, influence of the angle of attack profile on performance of propulsion is considered. Four prevalent profiles are evaluated by simulation of their effects on motion of foil in details. As general equation to be governed by substituting several parameters in basic equations is nonlinear function, a simple numerical method is established. All parameters are calculated in each step and then are referred to basic relations to evaluate results. Subsequently, overall integral of force is taken over time duration to get mean force. Results for each profile are compared with experimental data for validation of numerical method being used in this modeling. The considered angle of attack profiles are: (I) harmonic profile that due to simple harmonic motion in both heave and pitch motion. (II) Square wave profile that α_{max} is kept constant during heave and pitch motion. (III) Sawtooth wave that has ramp profile and (IV) cosine function. After consideration of performance and control of propulsion system, a modified profile with easy handling to control is proposed. This profile makes it possible to generate sufficient thrust relative to probability of controlling. Finally, use of each profile is characterized and with consideration of its thrust forces and device control, appropriate profile is specified so that performance of propulsor would approach to its higher value.

2. Physical Model

The main objective of present paper is control of angle of attack during flapping foil propulsion, intending to improve performance at moderate Strouhal numbers. On the point of control, it is possible to consider various types of profiles and mechanisms for propulsion and find out more information about quality of mechanisms and proper application of them. Consideration of mechanism also poses a challenge in design of controlling systems, which have fewer errors and be easy handling to control of dynamics. Fig. 1 shows the schematic of flapping foil, which is faced with free stream velocity U and are involved with two motions. One is heave motion $h(t)$ that provides frequent up and down motion and other is pitch motion $\theta(t)$ that causes rotational translation of foil around a bar being fixed to foil. For getting concept of kinematic of flapping foil, as before some parameters are also defined in Fig.2 .Here, U is to foil velocity and $\dot{h}(t)$ represents the heave velocity of flapping foil. With oscillating of foil, it would has pitch and heave motions instantaneously. Contribution of these motions causes foil to generate lift force and this force has two vectors. One of them that is parallel to direction of motion, provides thrust force for propulsion and other vector might be or not be useful. For instance, if it involves with gravitational effect it could be useful for flying; if it is accompanied with thrust in swimming it is disadvantage of propulsion. The net angle of attack $\alpha(t)$ seen by foil is a combination of two angles. One is physical pitch angle of foil $\theta(t)$ and second is angle of heave velocity $\varphi(t)$, which is the angle between to foil and total velocities. The total velocity is the net velocity to be seen by foil and involves in lift force generation. Fig.3 shows motion of foil during one cycle. Lift force for each position is also presented. This force is perpendicular to path of foil motion and it has its maximum value in centerline vicinity and its lowest value in peak of oscillating amplitude, h_0.

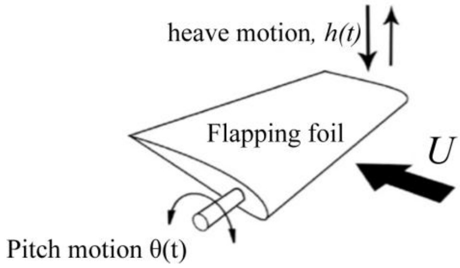

Fig. 1: Schematically diagram of oscillating foil

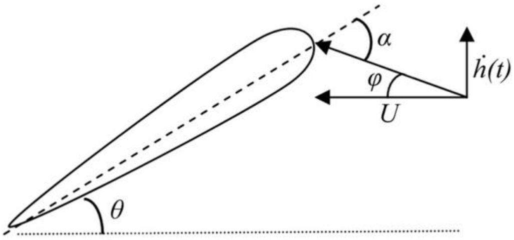

Fig. 2: Velocities and angles conducted to foil.

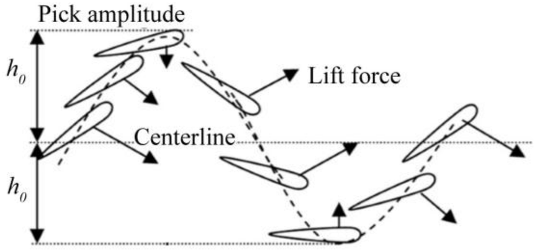

Fig. 3: Schematic of instantaneous lift force acting on foil during one oscillating period.

3. Kinematics of Flapping Foil

In flapping foil propulsion the angle due to heave velocity can be written as:

$$\varphi(t) = -\arctan\left(\frac{\dot{h}(t)}{U}\right) \tag{1}$$

Thus, the net angle of attack for foil is:

$$\alpha(t) = -\arctan\left(\frac{\dot{h}(t)}{U}\right) + \theta(t) \tag{2}$$

At low Strouhal number, the harmonic of $h(t)$ and $\theta(t)$ led to approximate harmonic $\alpha(t)$ and as Strouhal number increases, $\alpha(t)$ takes on additional components, which degrade the performance considerably. Read et al. (2003) performed a power-series expansion of tangent function to solve for higher harmonic of $h(t)$ that would flatten $\alpha(t)$. For given angle of attack and pitch trajectories, the heave motion can be found by integration of Eq. (2) over one cycle with respect to $\dot{h}(t)$. Thus:

$$h(t) = -U\int_0^T tan(\alpha(t) - \theta(t))dt \tag{3}$$

Therefore, with obtaining heave motion the mechanism of foil motion can be found, but in some cases, there are some strange relations that make it so difficult to control of propulsors. For harmonic profile the heave motion as function of time is $h(t)=h_0\sin(\omega t)$ and pitch control is $\theta(t)=\theta_0\sin(\omega t+\psi)$. Thus, it can be written as:

$$\alpha(t) = -\arctan\left(\frac{h_0\cos(\omega t)}{U}\right) + \theta_0\sin(\omega t + \psi) \tag{4}$$

For given α_{max}, U, ω and ψ it is possible to solve for absolute pitch angle amplitude θ_0. Read et al. (2003) demonstrates that θ_0 is limited by diverse phase angle of pitch motion with respect to Strouhal numbers. Additionally, he also found that variations in performance occur with changes in ψ. For $\psi = 90^0$ it provides a robust capability for high thrust and efficiency. Substituting Strouhal numbers in Eq. (4), it can be written as:

$$\alpha(t) = -\arctan(\pi St\,cos(\omega t)) + \theta_0\,cos(\omega t) \tag{5}$$

At low Strouhal numbers, arctangent is inconsequential, so it can be converted as:

$$\pm\alpha_{max} \approx -\pi St + \theta_0 \tag{6}$$

Eq. (6) is applicable at low Strouhal numbers but at higher ones, the arctangent function flattens, so that above equation represents a square wave added to an out of phase sinusoid. In the specified to foil velocity, with increasing the Strouhal numbers for harmonic motion of foil, heave velocity is induced by this variation and its value is increased, too.

4. Hydrodynamic Model

The selected hydrodynamic model was presented by Esfahani et al. (2013) and follows a 2D quasi-steady approximation which satisfies Theodorsen theory (1935). Some aspects are originated from aerodynamic model for flapping-wing flight (Delaurier, 1993). According to aerodynamic of lift body, the lift force due to flapping airfoil can be defined as:

$$L = \frac{1}{2}\rho\pi c C(k)\, sin\left(2\alpha|_{x_i=\frac{3}{4}}\right)\left[V|_{x_i=\frac{1}{4}}\right]^2 + \frac{1}{4}\rho U\dot{\theta}\pi c^2 \cos\theta + \frac{1}{4}\rho\pi c^2 \ddot{h}\cos\theta + \frac{1}{4}\rho\pi\dot{h}\dot{\theta}c^2 \sin\theta + \frac{1}{4}\rho\pi c^3\left(\left(\frac{1}{2} - x_0\right)\ddot{\theta}\right) \tag{7}$$

where x_o and x_i are location of pitching axis and incident velocity with respect to leading edge, respectively. k represents reduced frequency ($k=\pi fc/U$), V is total incident velocity, 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 and can be expressed in terms of Bessel functions of first and second kind, $H_j^{(2)}=J_j\text{-}iY_j$ .The total drag due to skin friction and pressure gradient of airfoil can be written as follows:

$$D = \frac{1}{2}\rho c\left[C_{DF}\left(U\cos\theta - \dot{h}\sin\theta\right)^2 + C_{DP}\left(U\sin\theta + \dot{h}\cos\theta + \left(\frac{1}{4} - x_0\right)c\dot{\theta}\right)^2\right]^{0.5} \tag{9}$$

where C_{DF} and C_{DP} are drag coefficients at α=0° and α=90°, respectively.

5. Propulsion Model

In most cases the thrust force made by oscillating foil is defined as a none-dimensional parameter that demonstrates quality of motion. This parameter is mean thrust coefficient and is defined as follows:

$$C_T = \frac{\overline{F}_x}{0.5\rho U^2 cs} \tag{10}$$

where $\overline{F_x}$ represents the average thrust force, ρ is water density and c represents foil chord and s is the span. The average thrust force is defined as follows:

$$\overline{F}_x = \frac{1}{T}\int_0^T F_x(t)dt \tag{11}$$

where $F_x(t)$ is instantaneous force in thrust direction (X-direction), T represents duration on one cycle. The mean overall input power to make locomotion is defined as follows:

$$P = \frac{1}{T}\int_0^T F_y(t)\frac{dh}{dt}dt + \frac{1}{T}\int_0^T M_0(t)\frac{d\theta}{dt}dt \tag{12}$$

where $F_y(t)$ is instantaneous loss force (force in Y-direction), M is instantaneous torque exposed to foil. dh/dt and $d\theta/dt$ are derivatives of heave and pitch motion, respectively. Therefore, the mean power coefficient is defined as follows:

$$C_P = \frac{P}{0.5\rho U^3 cs} \tag{13}$$

6. Strouhal Number and Angle of Attack Profile

If objective is that the angle of attack does not exceed from specified value, pitch motion must be controlled. Effects of these variation caused angle of attack to lose its harmonic profile. Fig. 4 shows the angle of attack profile for α_{max}=15° at different Strouhal numbers. These profiles are obtained when the heave and pitch motions are determined as harmonic function. The profiles are very different for low and higher Strouhal numbers. At St=0.2, angle of attack profile is nearly cosine-type profile and has two slope changes in one cycle. At St=0.4

and its higher values (St=0.8) the angle of attack losses its harmonic shape and has six slope changes during one cycle. Desired function for Square $\alpha(t)$ is:

$$\alpha(t)=\begin{cases}\alpha_{max},0\le t<T/4\\-\alpha_{max},T/4\le t<3T/4\\\alpha_{max},3T/4\le t<T\end{cases} \tag{14}$$

This profile is useful when the angle of attack is wanted to keep in constant value. If this constant value is the angle, in which lift coefficient is the highest value, the foil provides it's the highest lift force during cycle of flapping. The function for Cosine $\alpha(t)$ profile is:

$$\alpha(t)=\alpha_{max}\cos(\omega t), \tag{15}$$

and the function of symmetric Sawtooth $\alpha(t)$ profile is:

$$\alpha(t)=\begin{cases}\alpha_{max}\left(1-\dfrac{4t}{T}\right),0\le t<T/2\\\alpha_{max}\left(\dfrac{4t}{T}-3\right),T/2\le t<T\end{cases} \tag{16}$$

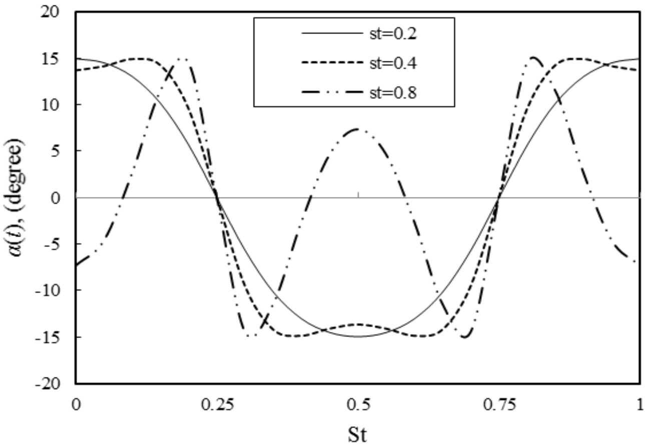

Fig. 4: Temporal evolution of angle of attack profiles with α_{max} =15º at different Strouhal numbers.

6. Essential parameters and assumptions

In this paper the motions of foil with respect to its angle of attack profiles are simulated and then thrust forces are obtained to consider of which profile has higher thrust force and better maneuverability. For validation theoretical results are compared with experimental ones. Next, a modified angle of attack profile for Square $\alpha(t)$ is developed and then its performance is evaluated. For this modeling NACA0012 foil is considered and other parameters including as follows:

1. Towing velocity U=0.3-0.5 m/s, leading to Re ~ 30000-500000;
2. Strouhal numbers St=0.2-0.7;
3. Chord c=0.1m and Span s=0.6m
4. Heave chord ratio h_o/c=0.5-1;
5. Maximum angle of attack α_{max} =15º;
6. Phase angle for pitch motion ψ =90^0.

In this study some assumptions have been made. These assumptions make the model easier and reduce calculations. On the other hand, this simplification leads some errors in results and causes modeling to not follow real phenomena. However, after simulation the results would be compared with other modeling and experimental results. In this model the towing velocity which is faced with flapping foil has uniform and laminar flow. Furthermore, the model is considered in position, where the effect of Fraud number is negligible. Fraud number has close relation with effects of water surface and walls of experiment water tank. It is worthy to mention that according to experimental data for NACA0012, at low angle of attack the changes of lift coefficient are about linear. Thus, relation between lift coefficient and angle of attack is taken as a linear function in this modeling.

6. Validation Study

Prior to conducting a detailed computation, present work is tested along with a series of validation cases to verify the capability of present modeling in prediction of results which is reasonable. As the objective is prediction of thrust, comparisons with existing experimental results can cover obtained instantaneous thrust and lift forces and mean thrust coefficients for each angle of attack profile. Fig.5 presents comparison of thrust coefficients in present work with experimental results performed by Anderson et al. (1998), Read et al. (2003) and Schouveiler et al. (2005). The foil has both harmonic heaving and pitching motions with heave chord ratio h_o/c=0.75, towing velocity U=0.4, phase difference between heaving and pitching ψ =90º and maximum angle of attack α_{max} =15º. As indicated in the figure, both experimental and modeling results show that thrust coefficient is increased with increasing St. Experimental results by Anderson et al. (1998) present more thrust value rather than those of two other experimental results. In experiments, including Anderson et al. (1998), the thrust is obtained by measuring the momentum deficit or surplus downstream of body. This technique may cause errors when velocity measurements are taken at plane not sufficiently far downstream of oscillating body where the wake eddies are still coherent (Young and Lai, 2004).

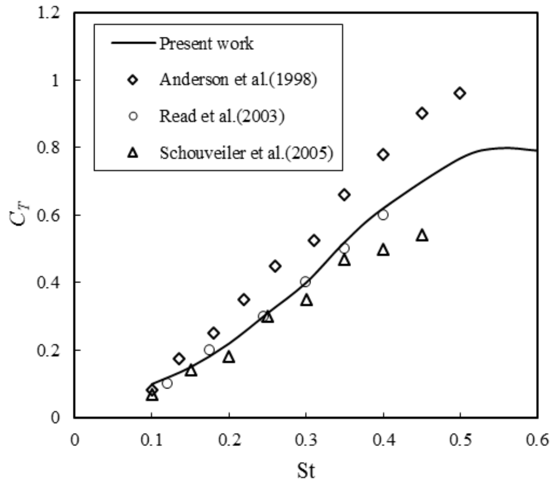

Fig. 5: Comparison of present computation with experimental results by Anderson et al. (1998), Read et al. (2003) and Schouveiler et al. (2005) with h_o/c=0.75, U=0.4, ψ =90º and α_{max} =15º.

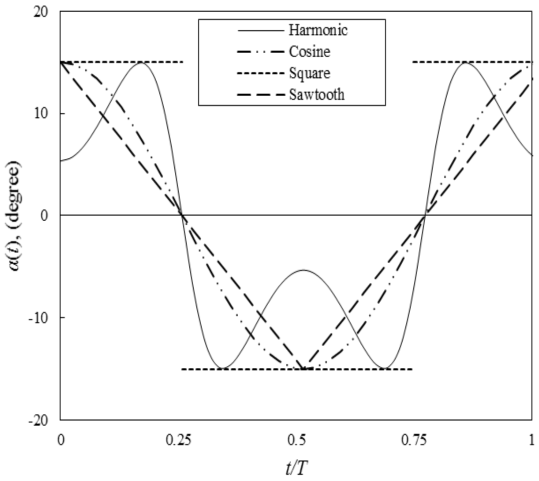

Fig. 6: Different angle of attack profiles at St=0.6.

3. Results and Discussion

In this section the effect of diverse angle of attack profiles on hydrodynamic performance of flapping foil are investigated. Fig. 6 shows various angle of attack profiles at St=0.4. Square $\alpha(t)$ has constant value with two discontinuities in T/4 and 3T/4. Sawthooth $\alpha(t)$ has ramp variations with moderate slope but a keen change in T/2. Harmonic and cosine angle of attack profiles are nearly similar at low St, but as it is shown here, this harmonic $\alpha(t)$ is belonging to St=0.4.

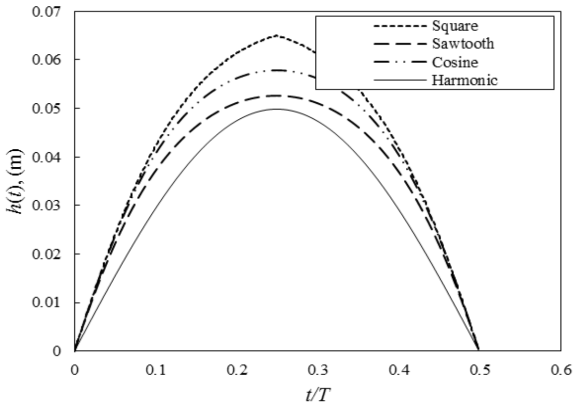

Fig. 7: Profile of heave motions for different angle of attack profiles with f=3, U=0.5, ψ =90º and α_{max} =15º.

As mentioned, velocity profile for Square $\alpha(t)$ has discontinuity, which poses an infinite acceleration in heave motion and this portion is defined as steep zone. This defect makes it hard for controlling of functions with such responses. The purpose to resolve this problem is to modify Square $\alpha(t)$. As shown in Fig. 3, lift force in peak of oscillating amplitude has insignificant effect on propulsion and it is known as loss force. If created force in this zone is neglected for Square $\alpha(t)$, the sharp changes in velocity profile are omitted. But the question is posed during this modification is that how much the slope of steep zone can be made smoother until it does not have any sensible changes in thrust forces. In addition to desirable thrust force, it must have feasible condition to control of system with ease. For answer to this question, a parameter that shows modified profile of steep zone is determined and this is defined as follows:

$$M(t) = \alpha_{max} \cos\left(\frac{\omega}{\beta} t - \left(\frac{1-\beta}{\beta}\right) \right) \tag{17}$$

where m represents modified profile in steep zone and β is slope factor. This means that change of slope in steep zone occurs in $(1\pm\beta)\ T/4$ and $(3\pm\beta)\ T/4$. When β is zero, it does not have any changes in angle of attack profile and it provides Square $\alpha(t)$. But when β is equal to one, a cosine profile is provided. Fig. 8 demonstrates modified angle of attack profile and its heave acceleration at St=0.4 for different slope factor. Fig. 8a presents results when slope factor is approximately zero and this leads square $\alpha(t)$. Heave acceleration of foil has infinite points in $T/4$ and $3T/4$. Fig. 8b and Fig. 8 display the effect of slope factor on angle of attack profile and heave acceleration. As it is shown, with increasing the slope factor, steep zones of angle of attack profile vanish and a mild behavior in heave acceleration occurs. Fig.8d presents the results for β=1 and this value leads to $\cos\alpha(t)$.

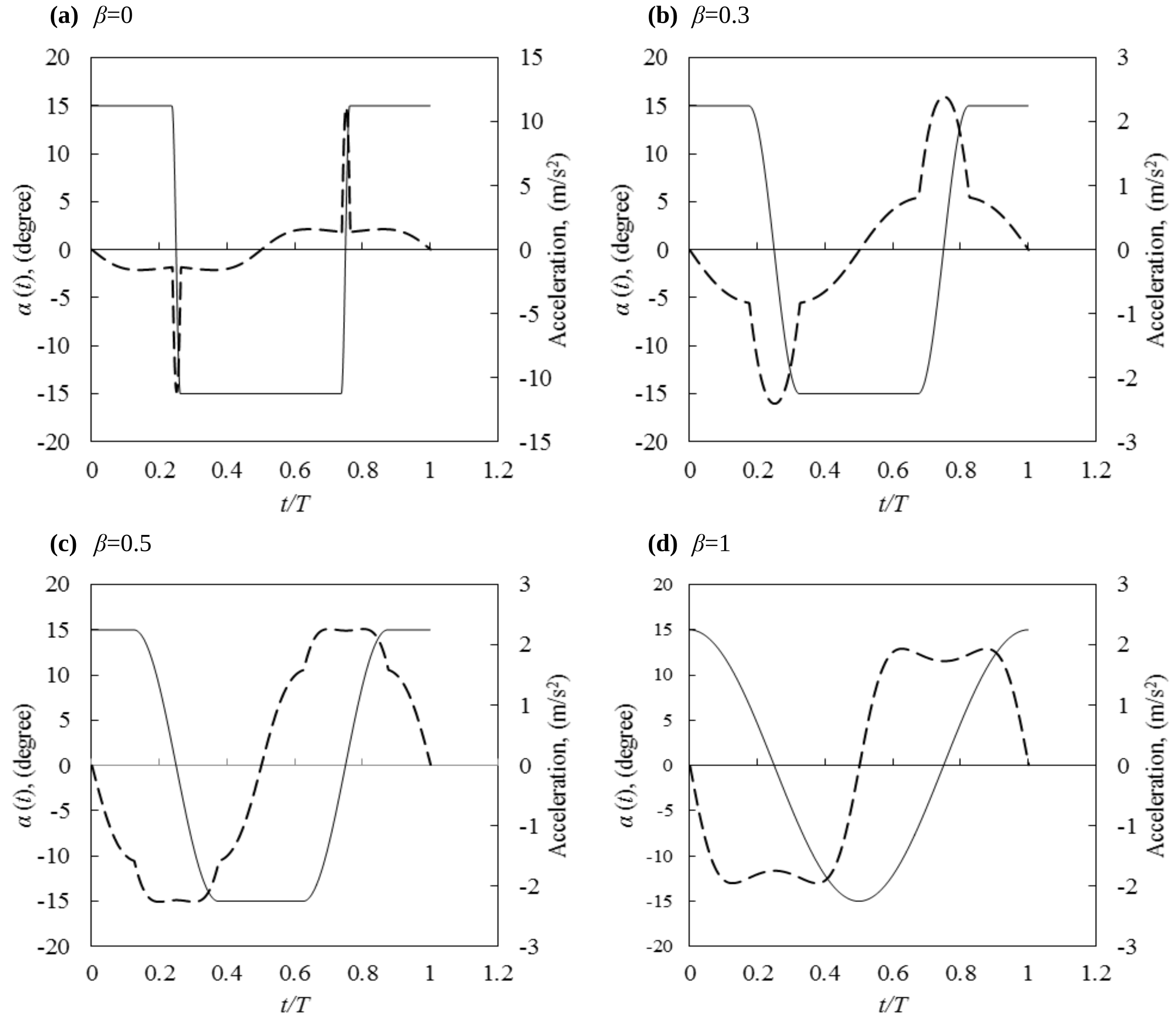

Fig. 8: Modified angle of attack profile (──) in different slope factors and heave acceleration (─ ─) for modified angle of attack profiles at St=0.4.

Fig. 9 presents counters of slope factors at different St with heave chord ratio h_o/c=1, towing velocity U=0.3, phase difference between heaving and pitching ψ =90º and maximum angle of attack α_{max} =15º. The line denoted by "0" shows proportion of thrust force for modified $\alpha(t)$ to that of Square $\alpha(t)$. At β=0 the modified $\alpha(t)$ is Square $\alpha(t)$ and its proportion is constant and proportional to 1. The line denoted by 1 (β=1) is belonging to Cosine $\alpha(t)$ and shows that the amount of thrust force for Cosine $\alpha(t)$ is always lower than that of Square $\alpha(t)$. Fig. 9 helps to identify proper range of slope factor for easy handling to control of system with respect to demanded thrust forces. In specified range of slope factors, the maximum β is proper choice because with increasing the slope factor, the changes of foil acceleration become moderate and flapping foil could be easily controlled. On the other hand, with increasing the slope factor, thrust forces will be decreased. Thus, appropriate ranges of slope factors are related to range of thrust forces, in which those thrust forces will not decrease significantly. For example, Table-1 is provided to show how determination of a proper slope factor β is possible. It is assumed that the amount of mean thrust must be not decreased more than 10%. At St=0.2, with increasing the slope factor, the mean thrust of modified profile decreases slightly and with approaching to approximately one, this mean thrust will decrease considerably. As a result, the best choice for slope factor at St=0.2 is in 0.1-0.3. On the point of proper selection, the easier technique to control of propulsion appears in higher slope factors. On the other hand, gradient of thrust is not significant in this range. Thus, with respect to sensitivities, a proper choice is available in specified range. At St=0.4, with increasing the slope factor, proportion of mean thrust coefficient decreases moderately relative to St=0.2 and it seems that proper slope factor is in the range of 0.1-0.5. At higher Strouhal numbers (St=0.6), such as two past descriptions, with increasing slope factor the mean thrust coefficients proportion decreases by a slight slope but in higher slope factor (β>0.5) the proportion of mean thrust coefficient decreases sharply. It is evident that for St=0.6 the proper range of slope factor is in 0.1-0.7. Thus, the conclusion can be drawn that at high St the range of appropriate slope factor expands and with increasing of this parameter (β), it is possible to operate easily relative to other St. Consequently, proper slope factors are 0.3, 0.5 and 0.7 for St=0.2, St=0.4 and St=0.6, respectively.

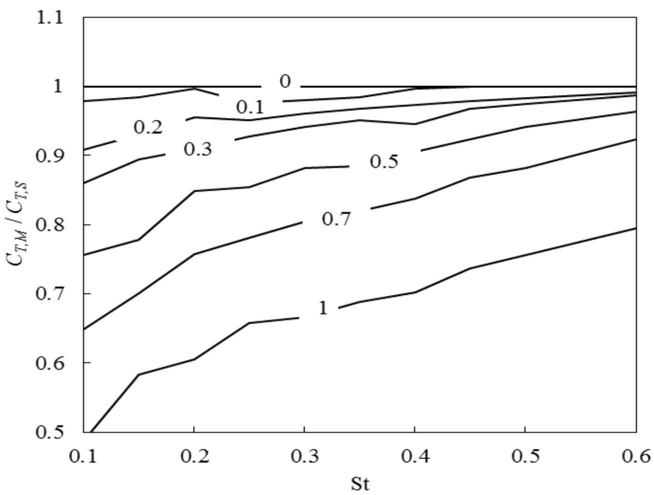

Fig. 9: Contours of slope factor for U=0.4, ψ =90º and α_{max} =15º. $C_{T,M}$ is thrust coefficient for modified $\alpha(t)$ and $C_{T,S}$ is thrust coefficient for Square $\alpha(t)$.

To consider which angle of attack profile is useful and reliable in different towing conditions and when it is appropriate to use modified angle of attack profile, the results must be evaluated. These results are gathered in two diagrams in Fig.10 to show how it is possible to consider these profiles. Fig. 10a presents thrust coefficients for each angle of attack profile in different St. The thrust coefficients are divided by square St, so that detection of results would be more easily. At lower Strouhal numbers (St<0.5) the thrust coefficient of Harmonic $\alpha(t)$ is more than those of Cosine and Sawtooth angle of attack profiles but its value is lower than Square $\alpha(t)$. Therefore, the conclude can be drawn is that at lower St the Harmonic and Square $\alpha(t)$ provides more thrust rather than Cosine and Sawtooth $\alpha(t)$. At higher Strouhal numbers (St>0.5), Harmonic $\alpha(t)$ generates the lowest thrust and other profiles have better performance with respect to their St. It is shown that Cosine $\alpha(t)$ produces the higher thrust values after Square $\alpha(t)$. If use of Square $\alpha(t)$ is not possible (because of controlling problems) and higher thrust values are demanded, it is advised that the best choices for cover these conditions are Cosine $\alpha(t)$ and modified angle of attack profile. For finding out which of them has better output, considering Fig.8b is

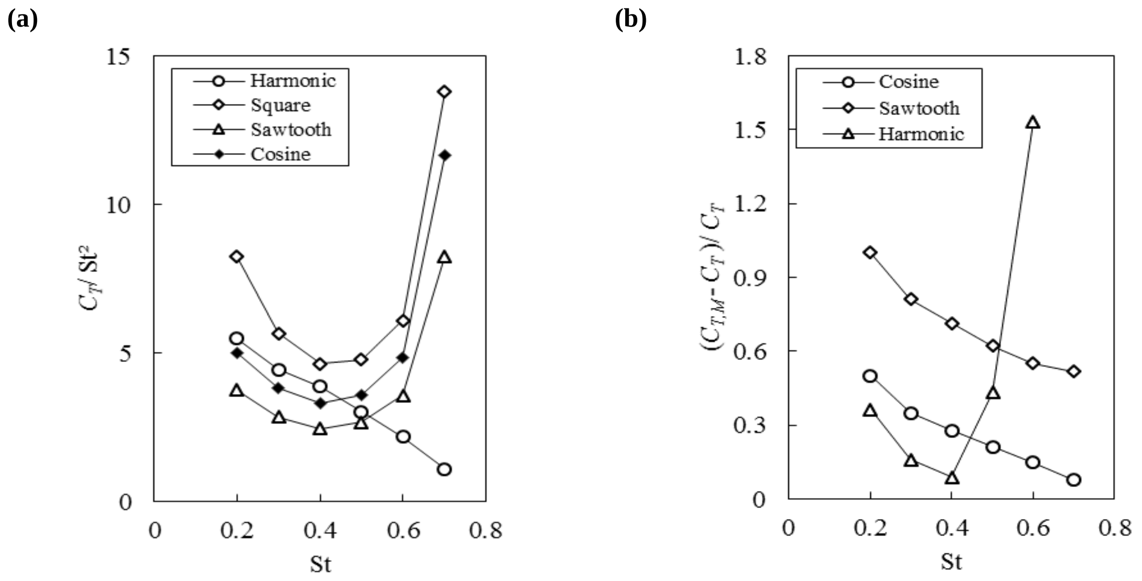

Fig. 10: Selection of angle of attack profile in order to produce sufficient thrust in different conditions with assumption of $(C_{T,S}-C_{T,M}) \leq 0.1C_{T,S}$ in which, $C_{T,M}$ is thrust coefficient of modified profile and C_T is thrust coefficient for other $\alpha(t)$. (a) Comparison of thrust to be produced by different angle of attack profiles in same conditions. (b) Proportion of thrust for modified angle of attack profile relative to other $\alpha(t)$.

one of the best ways to consider requirements. Fig. 10b demonstrates the proportion of mean thrust values of modified $\alpha(t)$ and Harmonic, Cosine and Sawtooth $\alpha(t)$ with respect to St. Thrust values of modified $\alpha(t)$ is more than others and these values are deducted with increase in St. Modified $\alpha(t)$ has sufficient thrust relative to Sawtooth $\alpha(t)$ and its minimum proportion is 51%. But at higher St, magnitude of thrust for modified $\alpha(t)$ are 14% and 7% more than that of Cosine $\alpha(t)$ at St=0.6 and St=0.7, respectively. On the other hand, Hover et al. (2004) demonstrated that efficiency of Cosine $\alpha(t)$ is in higher value relative to Harmonic, Square and Sawtooth angle of attack profiles. Thus it must be considered to know which parameter (efficiency or thrust force) can cover other and with reference to this parameter, it is possible to choose proper angle of attack profile. As the objective of present work is production of the higher thrust for high speed locomotion, the thrust value is preferred rather than efficiency because as mentioned earlier, higher thrust force is produced in patterns with low efficiencies. As Harmonic $\alpha(t)$ provides a simple motion relative to other angle of attack profiles at St=0.4 the mean thrust value of modified $\alpha(t)$ is 5% more than that of Harmonic $\alpha(t)$. Thus, use of Harmonic $\alpha(t)$ rather than modified $\alpha(t)$ is more desirable because of easy function of heave motion for Harmonic $\alpha(t)$.

7. Conclusion

In this study the effect of angle of attack profile on performance of flapping underwater vehicles is considered. Four different profiles are specified and based on the maximum produced thrust, the evaluation of profiles are done. It is shown that the maximum thrust production is belonged to Square profile but application of this profile would be faced with some controlling problems. Thus, a modified angle of attack profile is proposed and it benefits relative to other profiles are considered. It is demonstrated that the proposed profile have notable thrust production ability with easy handling to control and it can be used in wide range of steady propulsion conditions.

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