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ENHANCEMENT ON PROPULSION PERFORMANCE: MODIFYING ANGLE OF ATTACK PROFILE

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In this paper, numerical investigation was conducted for an oscillating NACA0012 foil combining the pitching and plunging motions. The plunging follows a sinusoidal motion while the pitching trajectory is controlled by achieving the resultant effective angle of attack (AOA) to be a harmonic cosine form. Computations were conducted over a range of the Strouhal number (*St*), different maximum effective AOA and different phase difference between pitching and plunging (ψ). Results show that, at higher *St*, significant improvement on propulsion performance has been achieved when the effective AOA profile maintains a harmonic cosine form by controlling the pitching motion of the foil.

Keywords: Oscillating foil; propulsion performance; effective angle of attack; pitching motion.

1. Introduction

Although there is a large amount of literature published[1–6] for an oscillating hydrofoil which mimics the flying bird and swimming fish, the detailed investigation on how the effective angle of attack profile affects the propulsion performance is less matured. For a coupled pitching/plunging oscillating motion, the instantaneous AOA $\alpha(t)$ is composed of instant pitching angle $\theta(t)$ and equivalent AOA contributed from plunging motion $-\arctan(\dot{h}(t)/U_\infty)$, i.e.

$$\alpha(t) = -\arctan(\dot{h}(t)/U_\infty) + \theta(t)\,. \tag{1}$$

Here the sinusoidal motions of plunging and pitching are expressed as:

$$h(t) = h_0 \sin(2\pi ft)\,,\ \theta(t) = \theta_0 \sin(2\pi ft + \psi) \tag{2}$$

with h_0 and θ_0 being the plunging and pitching amplitudes, respectively, ψ is the phase difference between plunging and pitching (pitching leading plunging), and f is the oscillating frequency which is related to the reduced frequency k by $k = \omega c / 2U_\infty = fc\pi / U_\infty$ where c is the chord length and U_∞ is the upstream velocity.

Previous studies have shown that, below a certain Strouhal number ($St = 2h_0 f/U_\infty$), the thrust force induced by oscillating foil and the required input power increases with St. Beyond this point, however, the thrust decays while the input power retains the increasing trend. As a result, the propulsion efficiency which is a ratio of thrust force to input power presents a fast decreasing with the increasing St. This critical frequency depends on five independent parameters of coupled pitching/plunging motions, i.e. pitching amplitude, plunging amplitude, phase angle difference between plunging and pitching, oscillation frequency and the upstream velocity.

Recent experimental work of Read *et al.*[3] and Hover *et al.*[4] on an oscillating NACA0012 airfoil have revealed similar observation. Moreover, for the first time, they explicitly pointed out that the reduction of thrust and propulsion efficiency at higher St is caused by the degradation of $\alpha(t)$ profile from sinusoidal form. The propulsion performance therefore can be improved by proper modification of pure sinusoidal oscillations either on plunging or pitching to recover the $\alpha(t)$ profile.

It is noticed that the limited previous studies on effective AOA profile entirely focused on the modification of the trajectory of *plunging* motion. As seen from Eq. (1), an effective has AOA contributions from both pitching and plunging motions. A natural question to be asked is whether this enhancement is still valid if we apply the change on the *pitching* motion while retain the same effective AOA profile. The objective of this study is therefore to numerically examine the effect of AOA profile on the propulsion performance of a NACA0012 airfoil by modifying the *pitching* motion.

2. Computational Method

The unsteady viscous flow around an oscillating airfoil is modeled by solving the 2D unsteady Navier-Stokes equations based on a compressible solver at a low Mach number. The code is based on a finite volume method with multi-block and multigrid features. The basic numerical method in this paper follows that described in detail by Xiao and Liao.[5] For modeling the present oscillating foil, all computations are conducted at the free-stream Mach number Ma = 0.05. The Reynolds number investigated is around $\mathrm{Re} = 10^4$, therefore laminar flow is assumed.

In the present study, the cosine function of $\alpha(t)$ is expressed as

$$\alpha(t) = \alpha_{\max} \cos(\omega t)\,. \tag{3}$$

To achieve the resultant AOA satisfying above equation, the sinusoidal harmonic plunging motion is unchanged while the pitching profile is modified and determined by

$$\theta(t) = \alpha_{\max} \cos(\omega t) + \arctan(\dot{h}(t) / U_\infty)\,. \tag{4}$$

Computations are conducted for different St varying from 0.1 to 0.7, three different maximum AOA of $\alpha_{\max}$ = 10°, 15° and 20° and three phase angles ψ = 80°, 90° and 100°. The plunging amplitude is kept unchanged with $h_0 = 1.0$. For convenience, the case with the combined motions of sinusoidal harmonic plunging and pitching is referred to the baseline here.

3. Results and Discussions

Due to the space limit, only parts of computational results are presented in this paper. Figure 1 shows the typical variations of thrust coefficient ($C_t = \overline{F} / 0.5\rho U_{\infty}^2 c$) and input power coefficient ($C_{ip} = \overline{P} / 0.5\rho U_{\infty}^3 c$) with *St* for the baseline and the modified motion at a fixed $\alpha_{\max}$ = 15° and ψ = 90°. For baseline, C_t increases with *St* before *St* reaches 0.4, and decays with further increasing of *St*. The C_{ip} curve reveals a monotonically increase with *St*. The decrease of C_t versus *St* in the range of $0.4 < St < 0.7$ is effectively prevented when the pitching motion is modified based on Eq. (4). The corresponding C_{ip} with the modified motion at fixed *St* is slightly increased compared to that with the baseline. Significant improvement on the propulsion efficiency $\eta = C_t / C_{ip}$ is clearly demonstrated in Fig. 2. As seen from the figure, with the modification on pitching motion, η almost keeps a constant over a wide range of *St*.

To understand the mechanism of AOA effect on propulsion performance, we plotted the effective AOA variation with baseline motion in one oscillating period for different *St* in Fig. 3. For smaller *St* like *St* = 0.15, AOA profile shows a simple harmonic feature with one peak value in one period. However, AOA profile becomes flattened when *St* is increased to 0.35. With *St* further increasing to 0.52, more than one peak values are observed which is believed to be the reason of degradation on thrust and propulsion efficiency at higher *St*. This becomes more and more apparent when *St* is increased to much larger values like 0.6 and 0.7.

As aforementioned, in order to improve the thrust and propulsion efficiency, effective AOA profile is imposed by using a cosine function with its maximum effective AOA kept the same as that of the baseline motion. The modified AOA profile and corresponding pitching motion to achieve this cosine function are shown in Fig. 4. Compared to the baseline pitching motion, the modified pitching profile is flatter and closer to square wave with its amplitude being slightly smaller than that of the harmonic sinusoidal motion. The effective prevention on multiple appearances of the AOA peaks leads to the recovery of degradation on thrust and propulsion efficiency.

4. Conclusion

In this study, we conducted a numerical computation on investigating the effect of effective AOA profile on the propulsion performance of a NACA0012 oscillation foil. Different from the conventional combined sinusoidal pitching and plunging motion, the pitching motion is modified to achieve the resultant effective AOA to be a cosine function. Computational results show that, for the baseline motion, with increasing of *St*, the AOA profile deviates from simple harmonics which causes the degradation of thrust coefficient and propulsion efficiency at higher *St*. This is significantly prevented when the effective AOA is modified with a cosine function.

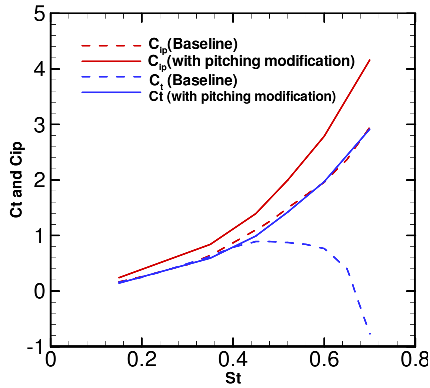

Fig. 1. (Color online) Comparison of the baseline and modified on C_t and C_{ip} vs *St*. ($\alpha_{\max} = 15°$, $\psi = 90°$).

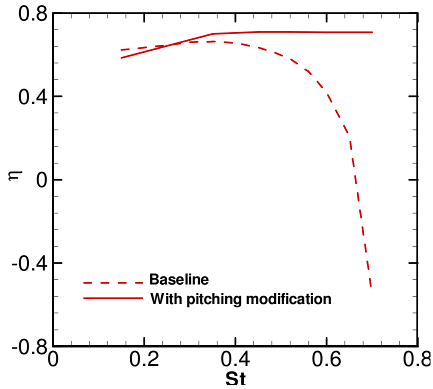

Fig. 2. Comparison of the baseline and modified on η vs *St*. ($\alpha_{\max} = 15°$, $\psi = 90°$).

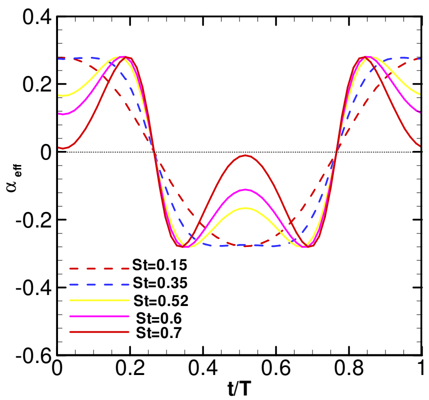

Fig. 3. (Color online) Variation of effective AOA profile with *St* in one oscillating period. (*Sinusoidal pitching and plunging* with $\alpha_{\max} = 15°$, $\psi = 90°$).

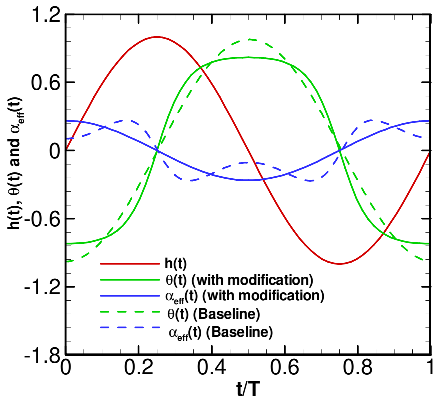

Fig. 4. (Color online) Variation of effective AOA profile with *St* in one oscillating period. (*Sinusoidal plunging and modified pitching* with $\alpha_{\max} = 15°$, $\psi = 90°$).

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