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Investigation of Effects of Strouhal and Reynolds numbers on Propulsive Efficiency of Plunging and Pitching Foils

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1. Introduction

Plunging and Pitching motions are inspired by flying and swimming animals and provide new insight into propulsive efficiency for the design of micro air vehicles (MAVs) and autonomous underwater vehicles (AUVs). Propulsive efficiency is often studied by nondimensional parameters, such as Strouhal (*St*) and Reynolds (*Re*) numbers.

Previous research has shown that the Strouhal number affects the wake dynamics and thrust generation [1,2]. The optimal Strouhal number for long-distance cruises has been investigated experimentally and numerically and occurs at *St* = 0.2 to 0.4 [3,4]. In addition, the Reynolds number effect causes the flow transition between laminar and turbulence, thereby affecting the force performance [5,6].

According to the definitions of *St* and *Re* numbers, the frequency *f*, plunging amplitude *A*, and flow velocity *U* can form different effects on fluid dynamics. Previous studies have investigated the effects of *St* and *Re* in a narrow range of *f* and *A*. The fluid dynamics remain unclear and need to be clarified in a wide range. The objective of the research is to investigate systematically the propulsive efficiency at varied *St* and *Re* numbers by altering the frequency *f*, plunging amplitude *A*, and flow velocity *U*. The range of the reduced frequency *k* is at *k* = 0.2 to 1.3; the nondimensional amplitude *h* occurs between 0.2 and 1.8; the *Re* number ranges from 2000 to 80000. The research provides an estimate to get a suitable kinematic within the various ranges from the point of view of optimal propulsion efficiency.

2. Methodology

We adopted the numerical method to solve the unsteady flow fields. The Reynolds-averaged Navier-Stokes (RANS) equations was employed as the governing equations as follows.

$$\nabla \cdot \bar{\mathbf{u}} = 0 \tag{1}$$

$$\frac{\partial \bar{\mathbf{u}}}{\partial t} + (\bar{\mathbf{u}} \cdot \nabla)\bar{\mathbf{u}} = -\nabla \bar{p} + \nu \nabla^2 \bar{\mathbf{u}} - \nabla \cdot \boldsymbol{\tau}, \tag{2}$$

where $\bar{\mathbf{u}}$ represents the mean component of the velocity vector, $\bar{p}$ is mean pressure, and $\boldsymbol{\tau}$ denotes the Reynolds stress tensor. The Shear-Stress Transport *k–w* model was applied to predict the flow surrounding the foil (NACA0012) due to the possibility of the separate flow. A commercial software ANSYS FLUENT was adopted for numerical simulation.

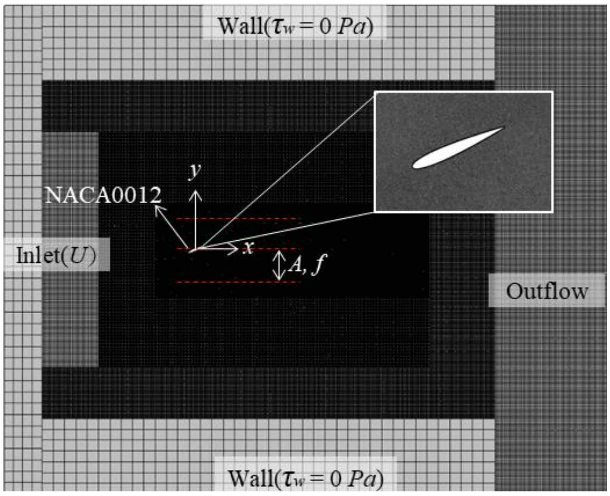

Figure 1: Computational mesh and its internal zone.

Based on previous work, we adopted a similar setting. The PREssure STaggering Option (PRESTO!) was selected as the pressure interpolation, and the second-order QUICK scheme was used in the momentum, turbulent energy equations. The Pressure-Implicit Split-Operator (PISO) method was chosen, which is highly acceptable in the transient flows. The computational domain is displayed in Fig.1. The total of mesh is about 900,000 cells. The inlet boundary is subjected to a velocity inlet condition. The pressure outlet is employed for outlet boundary. The upper and lower boundaries are set to walls. The surface of NACA0012 foil is no-slip condition. Relevant parameters are defined in Eq. (3). The thrust coefficient C_T, power coefficient C_P, and propulsive efficiency η is shown in Eq. (4),

$$Re = \frac{\rho U c}{\mu},\ St = \frac{fA}{U},\ k = \frac{fc}{U}\ ,h = \frac{A}{c}. \tag{3}$$

$$C_T = \frac{-F_x}{\frac{1}{2}\rho U^2 c},\ C_P = -\frac{F_y h' + M_z \theta'}{\frac{1}{2}\rho U^3 c},\ \eta = \frac{C_T}{C_P}, \tag{4}$$

where F_x, F_y are drag and lift respectively; c denotes chord length; h' and θ' represents plunge and pitching velocity; M_z is pitching moment; ρ is air density. The propulsive efficiency is the ratio of the mean thrust coefficient to the mean power coefficient over each cycle. The plunging and pitching motion are sinusoidal motions, and the pitching amplitude is fixed at $\theta_0 = 25^\circ$.

3. Results

The work is performed with varied *f*, *A*, and *U* to discuss the effects of *St* and *Re* numbers, which can be divided into two categories. Firstly, we choose fixed *k* and *h* to form *St*, which is used to reveal the *Re* effect. Secondly, we fixed *Re* to clarify the effects of *k* and *h* on propulsive efficiency.

3.1 Effect of *Re* at a fixed *St*

We choose a high reduced frequency *k* = 1 and low nondimensional amplitude *h* = 0.3 to discuss the effect of *Re*, which ranges from 2000 to 80000. The result indicates that while the flow field transits from laminar to turbulent, the propulsive efficiency can enhance gradually. The propulsive efficiency, however, increases slowly, as the *Re* increases over 20000. The result shows that intermediate and high *Re* are insensible to propulsive efficiency. Similarly, a low reduced frequency *k* = 0.2 and high nondimensional amplitude *h* = 1.5 are adopted to analyze the effect of *Re*. A similar effect is demonstrated. Note that although the *St* of the two categories is 0.3, low *k* and high *h* perform a better efficiency than that of the other category.

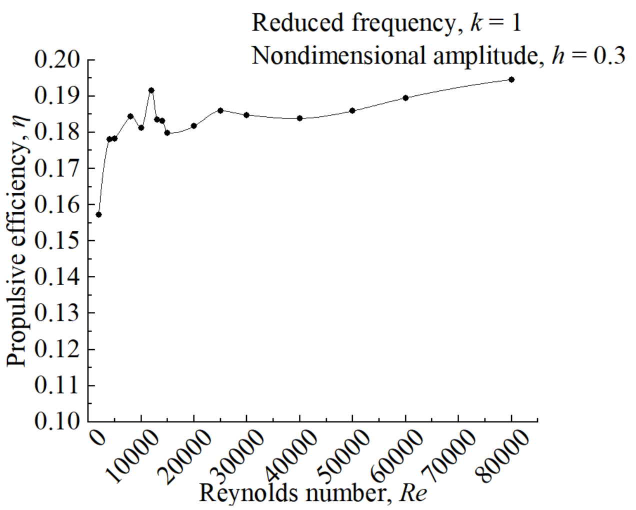

Figure 2: Propulsive efficiency with fixed high *k* and low *h* (*St* = 0.3) at various *Re*.

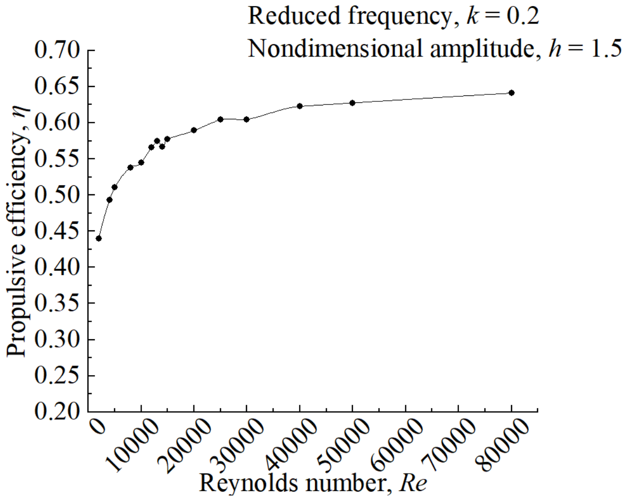

Figure 3: Propulsive efficiency with fixed low *k* and high *h* (*St* = 0.3) at various *Re*.

3.2 Effects of *k and h* at a fixed *St*

In Fig. 4, we use various *k* and *h* to form the same *St* = 0.3 and clarify the effects of *k* and *h* at three Re numbers. The result indicates that regardless of the Reynolds number, low *k* and high *h* have better propulsive efficiency. Furthermore, while the *k* and *h* are the same, the greater the Reynolds number, the greater the efficiency, which is consistent with the previous explanation.

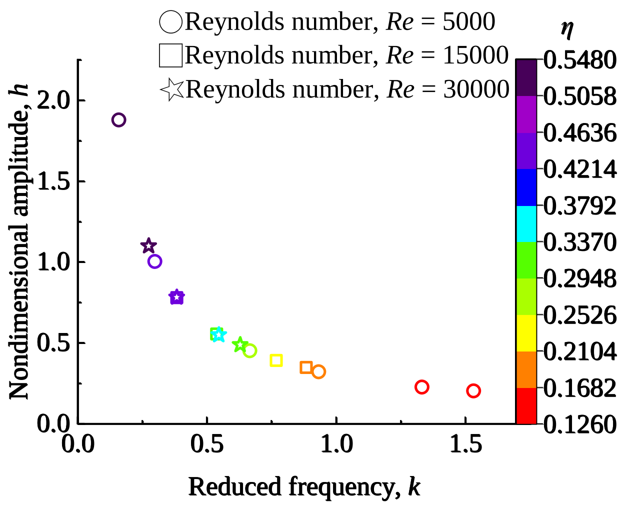

Figure 4: Propulsive efficiency for various *k* and *h* (*St* = 0.3) at the three *Re* numbers.

4. Conclusion

Our research interprets the effects of *Re* and *St* on propulsive efficiency by altering *f*, *A*, and *U*. Preliminary results show that *h* has a significant effect on propulsive efficiency compared with *k*. However, *k* has a remarkable effect on thrust and power coefficients. The analysis of the detailed flow structures is left for future work.

Acknowledgement

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