THRUST PRODUCTION OF A FLEXIBLE LOW-ASPECT-RATIO FOIL

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Summary We numerically investigate the hydrodynamic performance of a flexible rectangular foil pitching around its leading edge in a uniform free stream at Reynolds number 640. The 3D fluid–structure interaction is solved using an immersed-boundary method coupled with nonlinear structural mechanics of a thin plate. It is found that moderate structural flexibility significantly reduces the power requirement for the thrust production. The thrust force can be described the Strouhal number the foil regardless the plate deformation.

INTRODUCTION

A hydrofoil that undergoes heaving and/or pitching motions is often used as a simple representation of flapping wings to study the unsteady flow phenomena such as the leading vortex formation and vortex shedding in the wake. In addition, the pitching and heaving foil in an incidental flow is a reasonable approximation of the caudal fin of fish and can be used to study the thrust production of the fish fin. Substantial work has been done on the hydrodynamics of rigid pitching/heaving foils [1]. The unsteady wake behind the foil on average was found to be like a jet flow, and the vortices closely resemble the von Kármán vortex street behind bluff objects but have reversed rotation. In addition, the thrust efficiency is largely dependent on the Strouhal number. For the foil at low aspect ratios and three-dimensional flow, Buchholz & Smits [2] studied a rigid panel pitching around its leading edge in a free stream. They found that the thrust coefficient depends on both the Strouhal number and the aspect ratio and that the propulsive efficiency is sensitive to the aspect ratio when the span-to-chord ratio is less than 0.83.

In comparison to rigid foils, the study addressing the fluid–structure interaction of elastic foils with pitching and heaving motions is very limited. Existing studies are mainly limited to foils of large span-to-chord ratios and two-dimensional flows. For example, Heathcote & Gursul [3] investigated the effect of chordwise deformation on thrust generation and power consumption of an elastic foil in water tank. Moderate flexibility was found to increase the thrust efficiency compared to the rigid foil and an optimal flexibility may exist for given heaving frequency and amplitude. On the computational side, Zhu [4] assumed the flow around the flapping foil is inviscid and utilized a boundary-element method to solve the flow. Michelin & Llewellyn Smith [5] studied the effect of structural resonance on the thrust performance of a heaving foil. Potential flow was assumed in these works with incorporation of vortex shedding in the wake. Despite these previous works, the three-dimensional flow pattern and the thrust production of flexible pitching/heaving foils at low aspect ratios are still unknown.

MODELING APPROACH

As shown if Fig.1, We consider a thin, flexible rectangular panel that rotates around its leading edge sinusoidally with the pitching angle as $\alpha = \alpha_{\text{max}} \sin(2\pi f_{\text{freq}} t)$ where f_{freq} is the oscillation frequency, α_{max} is the maximum angle of attack. The uniform free stream velocity is U_∞, and the domain is unbounded. The panel is homogeneous and isotropic and has length L, width W, density ρ_s, thickness h, Young's modulus E, and Poisson's ratio ν_s. The bending displacement of the panel is arbitrarily, but the strain is assumed to be small so that the material still obeys the constitutive law of linear elasticity. The flow is governed by the viscous incompressible Navier–Stokes equations. No-slip and no-penetration conditions for the fluid are imposed on the plate surface, and the plate is subject to the hydrodynamic traction differential $\mathbf{f} = \left[\boldsymbol{\sigma}^{(+)} - \boldsymbol{\sigma}^{(-)}\right] \cdot \mathbf{n}$ where $\boldsymbol{\sigma}$ is the hydrodynamic stress tensor, $\mathbf{n}$ is the surface normal, and plus/minus denote the two sides of the plate. The nondimensional parameters governing the problems are the aspect ratio W/L, pitching amplitude α_{max}, reduced frequency $f = f_{\text{freq}} L/U_\infty$, Reynolds number $Re = U_\infty L/\nu$, mass ratio $\rho_s h/(\rho L)$, reduced stiffness $\varepsilon = EI/(\rho U_\infty^2 L^3)$ where $I = h^3/12$. In this study, the parameters are set at $W/L = 0.54$, $Re = 640$, and $\rho_s h/(\rho L) = 0.1$. To evaluate the performance of propulsion, we define the thrust coefficient C_T and power coefficient as $C_T = -F_x/\frac{1}{2}\rho U_\infty^2 WL$ and $C_P = -P/\frac{1}{2}\rho U_\infty^3 WL$, where F_x is the total force on the plate in the x-direction, and P is the total power spent for propulsion. The propulsive efficiency is $\eta = C_T/C_P$. The computational fluid–structure interaction is achieved by coupling a Cartesian-grid based immersed-boundary flow solver and a nonlinear finite-element structural solver. The numerical method has been described in our previous publications [6, 7].

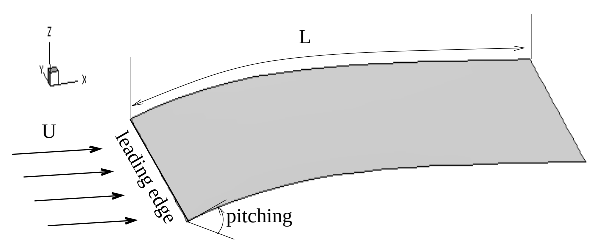

Figure 1. Schematic of the elastic panel pitching in a free stream.

RESULT

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Numerical simulations were performed for a range of pitching amplitude $\alpha_{\max}$ and reduced bending stiffness ε. Due to the chordwise deformation, the excursion of the foil, A^*, is amplified, and thus, the actual Strouhal number, defined as $St = f_{\text{freq}} A^*/U_\infty$, is larger compared to the rigid foil with the same pitching angle and frequency. When the frequency is low, the wake produced by the foil consists of two sequences of horse-shoe vortices as shown in Fig. 2, and their orientation is much like the inverse von Kármán vortex street produced by a rigid plate with equivalent excursion and amplitude.

Fig. 3(a) shows the thrust coefficient against the Strouhal number for a range of plate stiffness, $\varepsilon = 0.1$ to 5000. $\varepsilon = 5000$ is essentially the rigid case. For each set, the pitching amplitude $\alpha_{\max}$ is varied from $6°$ to $45°$. For most of the cases, the dimensionless frequency is $f = 1$. Some of the cases are run with $f = 2$. The results of all cases have been included. It can be seen that in the figure, except those with very large deformation (the elastic displacement close to the chord length of the foil), most of the data would fall on a single curve as a monotonic function of St. For highly flexible foils, e.g., $\varepsilon = 0.1$ and 0.25, the thrust may be reduced even if the Strouhal number is kept the same.

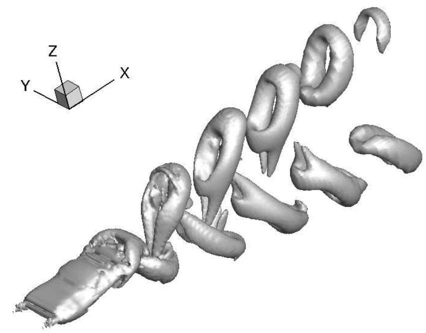

Figure 2. The vortical structures in the wake for a flexible plate pitching at $f = 1$, $\alpha_{\max} = 12°$, and $\varepsilon = 0.5$.

The propulsion efficiency η is shown in Fig. 3(b) for all the cases. For most of the cases with different plate stiffness, the best performance is found for St in the range 0.3 to 0.5. Below this range, the efficiency is reduced very quickly, and it turns to negative, i.e., the thrust becoming drag, as St goes to below 0.2. For high Strouhal numbers, the efficiency drops slowly. For $f = 1$, it can be seen that the efficiency for $\varepsilon = 0.5$ is significantly higher than the corresponding rigid case. Further increasing the flexibility would reduce the efficiency. For $f = 2$, the optimal rigidity takes place at $\varepsilon = 2.0$. The result is consistent with the scaling. That is, the deformation of the present foil is mainly due to the pitching motion of the foil, and the pressure force would roughly scale as the square of the pitching frequency. Thus, the foil with $f = 2$ and $\varepsilon = 2.0$ would experience a similar deformation pattern as the foil with $f = 1$ and $\varepsilon = 0.5$.

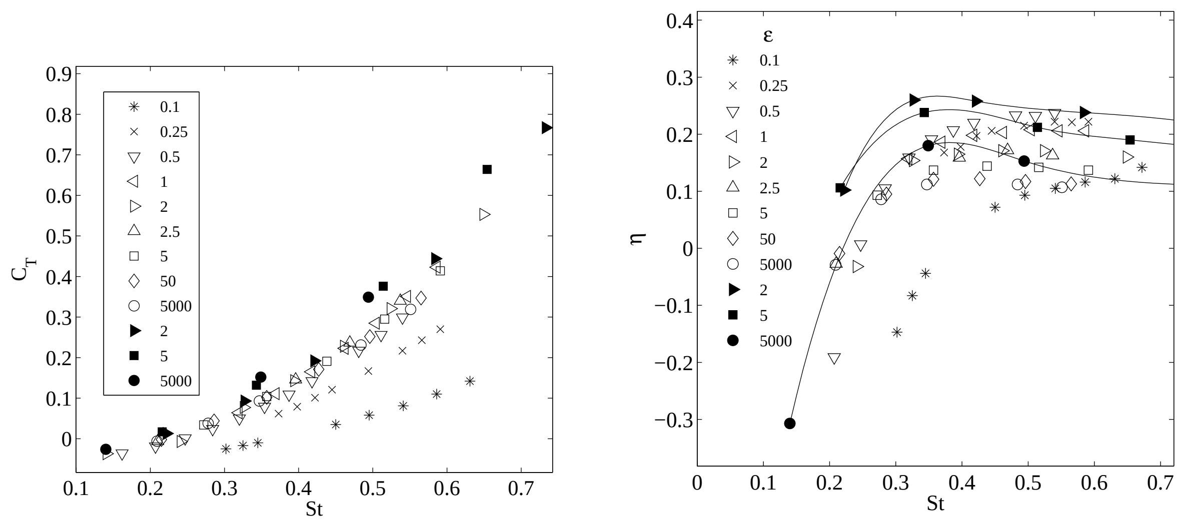

Figure 3. Thrust coefficient (a) and power efficiency (b) as functions St. Open symbols: $f = 1$; filled symbols: $f = 2$.

References

[1] M.S. Triantafyllou, A.H. Techet, and F.S. Hover. Review of experimental work in biomimetic foils. *Oceanic Engineering, IEEE Journal of*, 29(3):585–594, 2004.

[2] J.H.J. Buchholz and A.J. Smits. The wake structure and thrust performance of a rigid low-aspect-ratio pitching panel. *Journal of fluid mechanics*, 603(-1):331–365, 2008.

[3] S. Heathcote and I. Gursul. Flexible flapping airfoil propulsion at low Reynolds numbers. *AIAA J.*, 45(5):1066–1079, 2007.

[4] Q. Zhu. Numerical simulation of a flapping foil with chordwise or spanwise flexibility. *AIAA J.*, 45(10):2448–2457, 2007.

[5] S. Michelin and S.G. Llewellyn Smith. Resonance and propulsion performance of a heaving flexible wing. *Phys. Fluid*, 21:071902, 2009.

[6] H. Luo, B. Yin, H. Dai., and J. F. Doyle. A 3D computational study of the flow–structure interaction in flapping flight. *AIAA Paper 2010-556*, 2010. 2010-556.

[7] H. Luo, H. Dai, and P. Ferreira de Sousa. On the numerical oscillation of the direct-forcing immersed-boundary method for moving boundaries. *Computers & Fluids*. In press.