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[Extended Abstract]

Effect of non-uniform flexibility on hydrodynamic performance of pitching propulsors

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Introduction

Animals propel themselves efficiently and rapidly through a fluid using flexible appendages. While it has already been confirmed that flexible propulsors are advantageous to rigid ones in aquatic locomotion [1], we yet don't know how the structural properties, and more importantly the interactions between the fluid and structure and the resulting bending patterns, play a role in achieving the desired performance. The majority of the previous studies, both experimental and numerical, have either focused on lumped flexibility at a fixed location along the foil or employed uniformly flexible materials [1, 3, 2]. However, natural propulsors are made of complex materials with non-homogeneous flexibility. This study is a primary step toward understanding the role these functionally graded materials play in the propulsive performance of aquatic animals. Results of this study can also inspire design of innovative and non-traditional propulsors.

1. Problem Definition

All the numerical experiments are performed on a two dimensional foil where the leading edge of the foil is actively pitching with amplitude of 10 degrees. There is one or two flexible hinges along the chord modeled by torsional spring (figure1). The distance of the flexible hinge from the leading edge, normalized by the chord length, is quantified by flexion ratio, λ. The non-dimensional flexibility of the hinge is defined by eqn.1

$$\Pi = (1 - \lambda^2)\sqrt{\frac{\rho c^4 f^2}{k}} \quad (1)$$

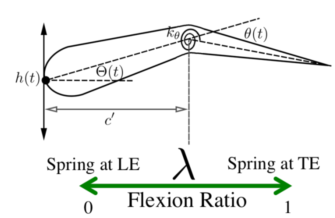

Figure 1. Schematic of the model

where ρ, f, c, and k respectively are the fluid density, pitching frequency, foil chord length, and the spring stiffness.

The flow over the foil is modeled using a two-dimensional potential flow method in which the flow is assumed to be irrotational, incompressible and inviscid. The fluid and structure solvers are strongly coupled via an Aitken relaxation method.

2. Preliminary Results

2.1 Single flexible hinge

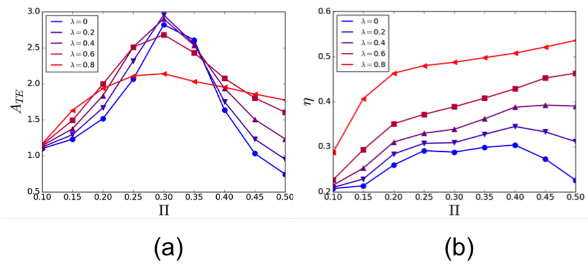

Figure 2. Trailing edge amplitude (a) and propulsive efficiency (b) versus Π for multiple flexion ratios.

Figure 2a shows the trailing edge amplitude as function of non-dimensional flexibility for 5 different flexion ratios. The trailing edge amplitude is maximum at resonance which occurs at $\Pi = 0.3$ for all flexion ratios.

The trend of changes in both C_t and C_p is similar to that of the trailing edge amplitude, with the peak occurring at the resonance. For small λ's, efficiency variations with Π shows two peaks before and after resonance, with the second peak being slightly larger than the first (figure 2b). Efficiency drops quickly after the second peak. This is not the case for large λ values where efficiency continues to increase monotonically reaching values as high as 50% or more ($\lambda = 0.8$). In general, at any given Π value, foils with larger flexion ratios have higher propulsive efficiency but smaller thrust coefficients.

2.2 Two flexible hinges

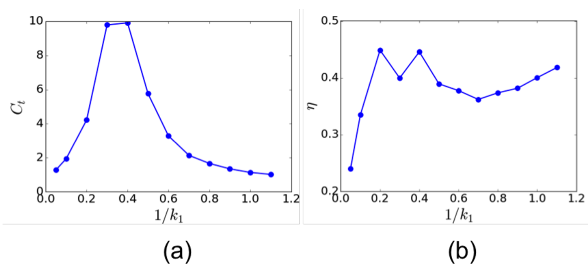

Figure 3. Trailing edge amplitude (a) and propulsive efficiency (b) versus Π for a foild with two flexible hinges at $\lambda = 03$ and 0.7.

In the previous section we showed that changing the bending patterns of a pitching foil via increasing its flexion ratio is the key to improving its propulsive efficiency. However, there is a trade off to this gain since smaller flexion ratios are required for larger force production. We hypothesize that combining multiple flexible hinges may be the key to gaining both in efficiency and force magnitude. To test our hypothesis, we repeated our numerical experiment on a pitching foil with two torsional springs located at $\lambda_1 = 0.2$ and $\lambda_2 = 0.7$.

Our results show that the magnitude of the thrust coefficient is larger than that of the single flexible hinge at $\lambda = 0.2$ or $\lambda = 0.7$ across all flexibility magnitudes tested here, except for very stiff hinges (figure 3a). The maximum efficiency reaches up to 45% which is significantly higher than the peak efficiency observed for a single flexible hinge at $\lambda = 0.2$ but slightly less than the peak efficiency for $\lambda = 0.7$(figure 3b).

Altogether, our preliminary results suggest that not only flexibility but more importantly the distribution of flexibility plays a key role in enhancing propulsive performance of pitching foils. Proper selection of flexibility distribution can result in improving both the thrust production capacity and the propulsive efficiency of pitching hydrofoils.

References

[1] Peter A Dewey et al. "Scaling laws for the thrust production of flexible pitching panels". In: *Journal of Fluid Mechanics* 732 (2013), pp. 29–46.

[2] Sébastien Michelin and Stefan G Llewellyn Smith. "Resonance and propulsion performance of a heaving flexible wing". In: *Physics of Fluids* 21.7 (2009), p. 071902.

[3] KW Moored et al. "Linear instability mechanisms leading to optimally efficient locomotion with flexible propulsors". In: *Physics of Fluids* 26.4 (2014), p. 041905.