EFFECT OF CHORD-WISE FLEXIBILITY ON PROPULSIVE PERFORMANCE OF OSCILLATING-FOILS

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ABSTRACT

Many modern engineering systems use biomimetics to replicate the high efficiency and maneuverability of animals that cannot yet be achieved by conventional propulsion systems. Oscillating foils, analogous to flapping wings or fins found in nature, provide one such solution, yet the widespread use of oscillating foils has not received major acceptance due to the inherently complex fluid-structure interaction.

We performed a parametric experimental study to quantify the effects of structural and kinematic properties of a flexible foil on its propulsive performance at a chord-based Reynolds number of 80,000. Multiple foils of the same shape but varied construction allowed explicit comparison of the effect of stiffness. Forces exerted on the foil were directly measured using a load cell and decomposed into thrust and efficiency values. Quantitative patterns of phase-averaged flow velocity and out-of-plane vorticity in the near-wake of the foil were obtained using particle image velocimetry (PIV). The combination of the direct force measurements and flow imaging allowed identification of an optimal combination of flexibility and kinematics of the foil that promoted generation of thrust-producing vortices while mitigating the effects of drag-inducing flow structures.

INTRODUCTION

The prevalence of flapping and oscillating wings found in biology warrants research into the possible benefits and uses of associated biomimetic technologies. Oscillating-foils have been proven to serve a broad range of applications, including clean energy extraction in tidal and wind flows, lift generation in micro-aerial vehicles, and thrust generation for aquatic locomotion, yet many fundamental questions remain unanswered [1, 2, 3]. When acting as a thrust generator, oscillating-foil designs propose an elegant alternative to traditional rotary propellers, which often rely on brute-force approaches to achieve their engineering goals. Rather, oscillating-foils combine the function of propeller, control device, and stabilizer while providing a high degree of agility, and often high propulsive efficiencies.
Despite growing research interest, wide-spread adoption of oscillating-foil systems by industry has been slow due to inherently complex fluid-structure interactions, and the intricacies of mechanical systems needed to provide appropriate kinematics. The foil’s shape, structural properties, operating kinematics, and operating environment are influential on system performance yielding a formidable parametric space to work with [4]. Among research into oscillating propulsion systems, relatively little work has been performed on studying the interactions of a foil’s flexibility and pitch kinematics, both of which have been shown to increase propulsive efficiency [5]. Natural designs, however, have inherently developed combinations of the two parameters.

To study how combinations of chordwise flexibility and pitching kinematics can be tuned for optimal system performance, physical foil prototypes of varied structural properties have been constructed and tested under a range of kinematic conditions. The current research encompasses experimental results performed in a recirculating water channel at a Reynolds number of 80,000. Forces exerted on the foil were directly measured and decomposed into thrust and efficiency values. Quantitative patterns of phase-averaged flow velocity and out-of-plane vorticity in the near-wake of the foil were obtained using particle image velocimetry (PIV) to study vortex development. The work expands upon a previous study by Richards [6], which considered only force measurements and heave-only kinematics.

**EXPERIMENTAL SYSTEM AND TECHNIQUES**

Experiments were performed in a recirculating water channel with a working cross section of 45 cm x 45 cm. The test section of the flow channel was closed with a lid to eliminate free surface effects. A slot in the lid allowed the foil mounting shaft to pass through. A schematic of the experimental apparatus is shown in Fig. 1.

Heave and pitch motions were controlled independently by separate servo motors, and position feedback is supplied by motor encoders. Both motion profiles were sinusoidal, with a phase difference between heave and pitch of 90° as shown in Fig. 2. A positive pitch angle is defined here as the direction of rotation that would cause the foil to turn towards the motion path, as shown. Some of the experiments used a negative pitch angle, which has the opposite orientation, as shown by the dashed foil shape in the figure.

A three-axis load cell, located below the pitching motor, recorded torque about the pitching axis, and forces normal to and tangent to the chord direction. Measured force values were decomposed into cycle averaged thrust and efficiency values, the definitions of which are provided in the nomenclature section. Forces were sampled at a frequency of 10 kHz over 20 oscillation cycles, and results were filtered and averaged to produce a statistically converged mean cycle. Forces exerted on the foil itself were isolated by removing inertial and hydrodynamic forces exerted on the mounting shaft and load cell, which were recorded by running separate experiments without the foil attached. Inertial forces felt by the foil itself were conservative in nature, and yielded no contribution to cycle-averaged performance metrics.

Fluid velocity at the midspan of the foil was measured using high-speed particle image velocimetry (PIV). The flow was seeded with tracer particles with a mean diameter of 10 μm that were illuminated by a pulsed Nd:YLF dual diode-pumped laser. Phase-averaged images were calculated by averaging 250 instantaneous velocity fields corresponding to the same phase of the foil’s oscillation. Only one side of the foil was illuminated by the laser sheet. The symmetrical nature of the foil’s motion allowed the flow structure on the dark side of the foil to be measured by inverting the appropriate phase on the bright side. I.e., images recorded on the illuminated side at a period t/T=0.75 were inverted and used to represent the flow on the dark side of t/T=0.25.

Two flexible foils, referred to as foils ‘A’ and ‘B’, and one rigid foil ‘R’ were used in experiments. All foils had a chord length of 200 mm and a span length of 140 mm, and the cross-sectional shape shown in Fig. 3. The flexible foils were constructed of silicon-rubber, and the rigid foil was constructed of a stiff plastic compound. Additionally, the flexible foil ‘A’ was reinforced with a thin stainless steel shaft and had a lead weight embedded at the trailing edge, as shown in Fig. 3. The flexible foil ‘B’ was only reinforced between the leading edge and the aluminum mounting shaft, allowing a stiff nose but flexible trail.

**FIGURE 1: EXPERIMENTAL CONFIGURATION, SHOWING FORCE MEASUREMENT AND FLOW IMAGING CONFIGURATION. WATER CHANNEL AND LID NOT SHOWN.**

**FIGURE 2: KINEMATIC DIAGRAM OF THE SINUSOIDAL MOTION OF THE FOIL.**
The non-standard cross-sectional shape was developed to facilitate the strip of lead weight enclosed at the trailing edge of foil ‘A’, allowing the inertia and resonant frequency of the foil to be varied. The resonant frequency was measured experimentally while the foil was submerged in water. Properties of the three foils are presented in Table 1. Further details may be found in ref [6], which was an experimental campaign on the same foils. In that study, Richards and Oshkai tested a larger variety of foils with heave-only motion. The current foil ‘A’ had the highest measured thrust and efficiency metrics. The rigid foil ‘R’ was not previously tested.

RESULTS
All experiments were performed at \( Re = 80,000 \) and with a heave amplitude of \( H_0/c = 0.1875 \), representing a regime of practical interest as highlighted by Richards and Oshkai [6]. Pitch amplitudes were varied from -10° to 20°, and Strouhal numbers were varied from 0.15 to 0.45. The results for measured thrust and efficiency of this parametric range are presented in Fig. 4 for each foil. The circular points in Fig. 4 represent points where data was recorded, and isocontours are interpolated between results to produce the visual maps. Cycle-averaged thrust coefficients and efficiencies are shown.

Contrasting trends were observed between rigid and flexible foils with regards to thrust generation. For the rigid foil, the largest thrust coefficients tended towards regimes of high pitch amplitude. Both flexible foils, rather, required negative pitch angles to achieve high thrust when operating at high Strouhal numbers. In these cases, although foils ‘A’ and ‘B’ were prescribed a negative pitch angle at the pitching axis, the trailing edge deformed significantly, effectively inducing a positive pitch orientation.

The effective angle of the trailing edge played an important role in thrust generation. An emphasis of this point is observed by foils ‘A’ and ‘B’ were of interest as highlighted by Richards and Oshkai [6]. In these cases, pitch angles to achieve high thrust when operating at high Strouhal numbers. In these cases, although foils ‘A’ and ‘B’ were prescribed a negative pitch angle at the pitching axis, the trailing edge deformed significantly, effectively inducing a positive pitch orientation.

The select case of \( \theta_0 = 0° \) and \( St = 0.35 \), foils ‘R’, ‘A’, and ‘B’ had respective efficiency values of 0.20, 0.30, and 0.31. Further, high efficiency values (as an example, consider the contour region of \( \eta > 25% \)) cover a larger region of the parametric map for the flexible foils, signifying a larger practical operating range. Overall, the measured efficiencies (up to \( \eta \approx 0.40 \)) are still lower than peak values found in nature, and this result is attributed to the low-aspect ratio of the foil, and low heave amplitudes [7].

The increase in thrust production generated by the flexible foil is apparent in Fig. 5, which shows thrust vectors consistently larger in amplitude than the rigid equivalent. At the limits of each heave cycle, a small net drag was seen, but thrust quickly developed and persisted until the opposite heave limit when the foil changes direction.

The lateral force, which is associated with power input and required energy to be input into the system. An inflection point, where the direction of force reversed, occurred slightly after mid-stroke of the foil (\( H/H_0 = 0 \)). Beyond this inflection point, the net lateral forces acted in the direction of motion and the system was able to recover energy from the motion. Foil ‘A’ had an inflection point later in the cycle than foil ‘R’, signifying

![FIGURE 3: THE FOILS’ CROSS SECTIONAL SHAPE. THE FOILS ROTATE ABOUT THE AXIS OF THE ALUMINUM SHAFT.](image_url)

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expense, or otherwise), a suitable level of flexibility effectively recreates the benefits of pitch kinematics. The increases in thrust generation by both flexible foils was not necessarily accompanied by a decrease in efficiency values, as has been seen in previous research campaigns. Rather, foils ‘A’ and ‘B’ showed reasonable increases in efficiency from their rigid counterpart. As an example, under the conditions \( \theta_0 = 0° \) and \( St = 0.35 \), foils ‘R’, ‘A’, and ‘B’ had respective efficiency values of 0.20, 0.30, and 0.31. Further, high efficiency values (as an example, consider the contour region of \( \eta > 25% \)) cover a larger region of the parametric map for the flexible foils, signifying a larger practical operating range. Overall, the measured efficiencies (up to \( \eta \approx 0.40 \)) are still lower than peak values found in nature, and this result is attributed to the low-aspect ratio of the foil, and low heave amplitudes [7].

At the lowest tested Strouhal numbers some high efficiencies are seen, in the range of 40%, however the associated thrust levels were low in this range and it is not seen as a practical operation range.

In comparison between the two flexible foils, the stiffer foil ‘A’ that had the embedded mass and stainless steel reinforcement generated more thrust at comparable efficiencies.

The increase in thrust production generated by the flexible foil is apparent in Fig. 5, which shows thrust vectors consistently larger in amplitude than the rigid equivalent. At the limits of each heave cycle, a small net drag was seen, but thrust quickly developed and persisted until the opposite heave limit when the foil changes direction.

The lateral force, which is associated with power input and recovery to the heave motion, is shown in Fig. 6. At the beginning of a cycle, the lateral force purely opposed motion and required energy to be input into the system. An inflection point, where the direction of force reversed, occurred slightly after mid-stroke of the foil (\( H/H_0 = 0 \)). Beyond this inflection point, the net lateral forces acted in the direction of motion and the system was able to recover energy from the motion. Foil ‘A’ had an inflection point later in the cycle than foil ‘R’, signifying

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differences in hydrodynamic forces, where in a purely inertial system the inflection point would be expected to occur exactly at the mid-stroke when the foil begins to decelerate.

PIV images reveal the flow fields around the foil and provide insight into some of the previously noted phenomena. Figures 7 and 8 provide phase-averaged PIV images for foils ‘R’ and ‘B’, respectively, under the conditions $\theta_0 = 0^\circ$ and $St = 0.35$. The development of flow structures is visualized at sequential phases $t/T = 0/8, 1/8, 2/8, and 3/8$, representing the first half of a symmetrical wake structure. It is noted that symmetrical motion of the foil allows information of the second half of the motion cycle to be inferred from the first half. For example, phase $t/T = 4/8$ is simply an inverted image of phase $t/T = 0/8$. This allowing flow structures to be tracked throughout an entire cycle from this image set.

FIGURE 4: THRUST COEFFICIENT AND EFFICIENCY MEASUREMENTS, AS A FUNCTION OF PITCH AMPLITUDE AND STROUHAL NUMBER, FOR EACH FOIL. BLACK DOTS REPRESENT EXPERIMENTAL DATA POINTS.

FIGURE 5: INSTANTANEOUS STREAMWISE FORCES MEASURED FOR FOILS ‘A’ AND ‘R’, FOR THE CASE $\theta_0 = 0^\circ$ AND $St = 0.35$. THE FOILS TRAVEL FROM RIGHT TO LEFT.

FIGURE 6: INSTANTANEOUS LATERAL FORCES MEASURED FOR FOILS ‘A’ AND ‘R’, FOR THE CASE $\theta_0 = 0^\circ$ AND $St = 0.35$. THE FOILS TRAVEL FROM RIGHT TO LEFT.
Hereafter, the terms upper surface and lower surface are used to refer to upper and lower sides of the foil in the frame of reference provided in the images. For the phases shown, the upper surface acts as the pressure side of the foil, and the lower surface acts as the suction side, but this is opposite for the second half of the cycle.

At phase $t/T = 0$ in Fig. 7, corresponding to the bottom of the heave cycle of the rigid foil, flow was attached to the lower foil surface except where a weak leading edge vortex (LEV) persisted from a previous cycle. As the heave motion continued the boundary layer on the lower side began to roll up into a new LEV, but the vortex did not convect downstream significantly before the foil reversed heave directions. The LEV further dissipated before it could directly influence the trailing edge vortex (TEV) development.

On the upper surface of the foil at phase $t/T = 0$ vorticity had started to shed over the trailing edge. Vorticity continued to shed along the foil and progressively developed into a trailing edge vortex that would become the dominant flow structure in the wake.

The flow dynamics around the leading edge for foil ‘B’ was very similar to that of the rigid foil, in terms of the LEV’s timing, strength, and size. This was a result of the leading edge of the flexible foil being too short to deform considerable, thereby maintaining a near 0° angle with respect to the freestream throughout the cycle. The leading edge of the rigid foil, of course, also maintained a 0° angle with respect to the freestream. The flexibility of the foil showed a larger influence on trailing edge wake dynamics. Shedding of vorticity from the upper surface was not observed until the phase $t/T = 1/8$. The resulting difference manifested itself in a vortex smaller in size but greater in strength than that observed on the rigid foil. Additionally, the wake generated by the flexible foil was observably wider than that of the rigid foil.

The effect of pitch on flow dynamics is partially realized in Fig. 9, which provides phase-averaged PIV images for foils ‘R’ and ‘B’ recorded for kinematics with $\theta_0 = -10^\circ$, $5^\circ$, and $15^\circ$. All images are provided for the same phase $t/T = 0.25$, and same Strouhal number $St = 0.35$.

It was apparent that neither pitch nor trailing edge flexibility had significant influence on leading edge flow dynamics; only minor differences in LEV size occurred between each of the six presented cases. The LEVs that did develop were small in each case and represented only a small portion of the overall flow structure.

More evident differences were observed in the trailing edge flow fields. In general, increasing pitch amplitude had an effect of delaying the development of the trailing edge vortex. This is observed by comparing cases of $\theta_0 = 15^\circ$ with cases of $\theta_0 = -10^\circ$, the later having a much more mature vortex in the wake at the same phase in the cycle.

Analysis of the results shows that the angle of the trailing edge had the largest influence on thrust generation. The previous force measurements showed that the rigid foil ‘R’, at $\theta_0 = 15^\circ$ and $St = 0.35$, had a cycle-averaged thrust coefficient of $C_T = 0.75$, while the flexible foil ‘B’ at $\theta_0 = -10^\circ$ and $St = 0.35$ yielded $C_T = 0.76$. The similarity in results is quite remarkable considering the $25^\circ$ difference in prescribed pitch angle. However, it was observed through measurements of the image that the trailing edge of the flexible foil deformed, and was actually oriented $15^\circ$ (within +/-1°). This observation suggests that an optimal angle
CONCLUSIONS

An experimental campaign was conducted to study the effects of chordwise flexibility of the performance of oscillating-foils acting as propulsion devices. Two flexible foils, of different stiffness, were compared against a baseline foil that was fully rigid. The amplitude of prescribed pitch motion was varied from -10° to 20°, and Strouhal numbers from 0.15 to 0.45 were tested. Although this experimental range represents a small portion of the formidable parametric space that governs oscillating-foil propulsion, some notable underlying trends were observed. In general, the flexible foils produced higher thrust values than their rigid counterpart, as well as higher propulsive efficiencies. Both flexibility and pitch amplitude had little effect on the dynamics and development of the leading edge vortex, which, under the current small heave amplitudes, was unable to develop strongly and was not a dominant flow structure. Trailing edge flow dynamics were observed to have stronger influences on performance. Specifically, an appropriate level of pitch applied to the trailing edge was seen necessary for high performance. The results were insensitive to method by which the pitch motion was induced, whether actively prescribed to the rigid foil or allowed to develop passively via flexible foil deformation. In particular, it was noted that the rigid foil operating without pitch performed poorly. If operating in a heave-only manner, and pitch was allowed to passively develop through foil flexibility, performance was drastically improved.

REFERENCES