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# Asymmetries of Flexible Foil Locomotion (Abstract)
# 4th International Symposium on Aero Aqua Bio-Mechanisms (ISABMEC 2009)

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## I. ABSTRACT

Without asymmetry, locomotion would be impossible. We look at the effects of asymmetry on flexible foils in oscillation and at the role asymmetry plays in thrust production. Asymmetries in time are considered by changing the kinematic profile of an oscillating foil, leading to vectored force production and implications for efficiency. The benefits of asymmetry in the flapping profile are shown to be dependent on the physical properties of the fin as well as the on the other kinematic parameters.

## II. INTRODUCTION

Looking to the larger ray species (Myliobatidae) for inspiration for underwater propulsion, we and other researchers [1-3] have noticed that asymmetry is a key factor in how these and other animals move. The upstroke and the downstroke take different amounts of time to be completed, and can even extend different amounts about the body. This is not uncommon: birds often exhibit an asymmetric power and return stroke motion in order to stay aloft in the low-density air. However, elasmobranchs that are nearly neutrally buoyant do not need this kinematic pattern to stay at a given height in the water. This leads us to study the effects of asymmetry in terms of thrust production in order to determine what possible hydromechanical advantages may exist.

## III. METHODS

Fins were cast in silicone rubber of two stiffnesses (Silastic 3481, tensile strength 4·6 MPa, 520% elongation at failure and 3483, tensile strength 3·5 MPa, 600% elongation at failure, Nottcutt UK) in two shapes, giving four fins; shown in Figure 1. The dynamic stiffness of the silicone rubbers used has not yet been computed. Both fins were cast to have the same planform area (1·44 x $10^{-2}$ $m^2$).

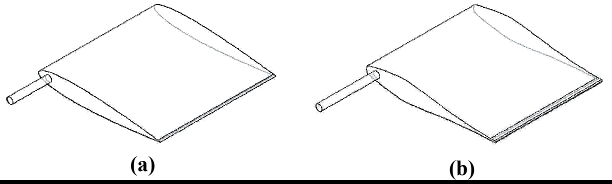

**Figure 1 – Fin shapes used in the experiments (a) the NACA0012 profile, (b) the biomimetic stiffness profile.**

The fins were attached to a servomotor-driven oscillator resting on a force rig suspended above a water tank (1·8 x 1·2 x 1·0 m). The oscillator unit rests on a pin at one end and on three force sensors (Sensortechnics FSS range) at the other end. The oscillator unit was weighted to pre-load the sensors to the middle their range. The sensors measured the components of force resolvable to the *x* and *y* directions, shown in Figure 2. The foils were made to oscillate sinusoidally back and forth while the control program changed the amplitude and frequency of oscillation. The preliminary experiments that looked at the effects of stiffness on the thrust produced by the NACA and 2D biomimetic foils are detailed in [4] by a colleague of the authors. In order to introduce kinematic asymmetry using the foils available, the duty cycle of the stroke was changed; from equal time to complete each half of the stroke to 15%, 25% and 35% of the time to complete one half. Hence at a frequency of 1 Hz, for example, a 25% flap would see the first half completed in 0·25 seconds (instead of 0·5 s). This introduced a "power and return" stroke. Data were recorded at 1000 Hz from the three force sensors and from a potentiometer measuring the real angular displacement.

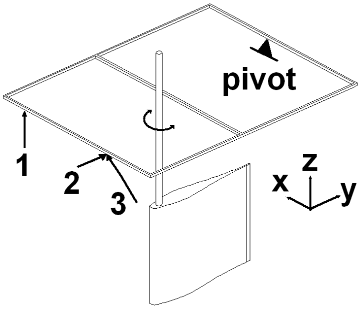

**Figure 2 – Three force sensors allow the component forces to be calculated for the oscillating rig.**

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The amplitude was varied from 2° to 20° in increments of 2° and the frequency ranged from 0·5 to 4 Hz, in increments of 0·5 Hz. The data sets of the symmetric cases are larger (ranges were higher and increments smaller) but the extra data make comparisons more difficult and so they are not shown.

## IV. RESULTS & DISCUSSION

The stiffness of the fins is a description of the gross physical characteristics of the silicone rubbers used and does not describe the effect of dynamic profile. With this in mind, we focus here on the effects of asymmetric kinematic profiles on each fin, with statements relating to the relative stiffness made tentatively.

MATLAB programs were created to process the data. The raw channel recordings covered 15 full flap cycles but in order to eliminate the high start up force peaks, the data from flap number 5 to flap number 15 were saved in order to look at the steady state forces. Component forces are calculated at this stage, averaged per cycle and it is from this condensed data set that the graphs are drawn.

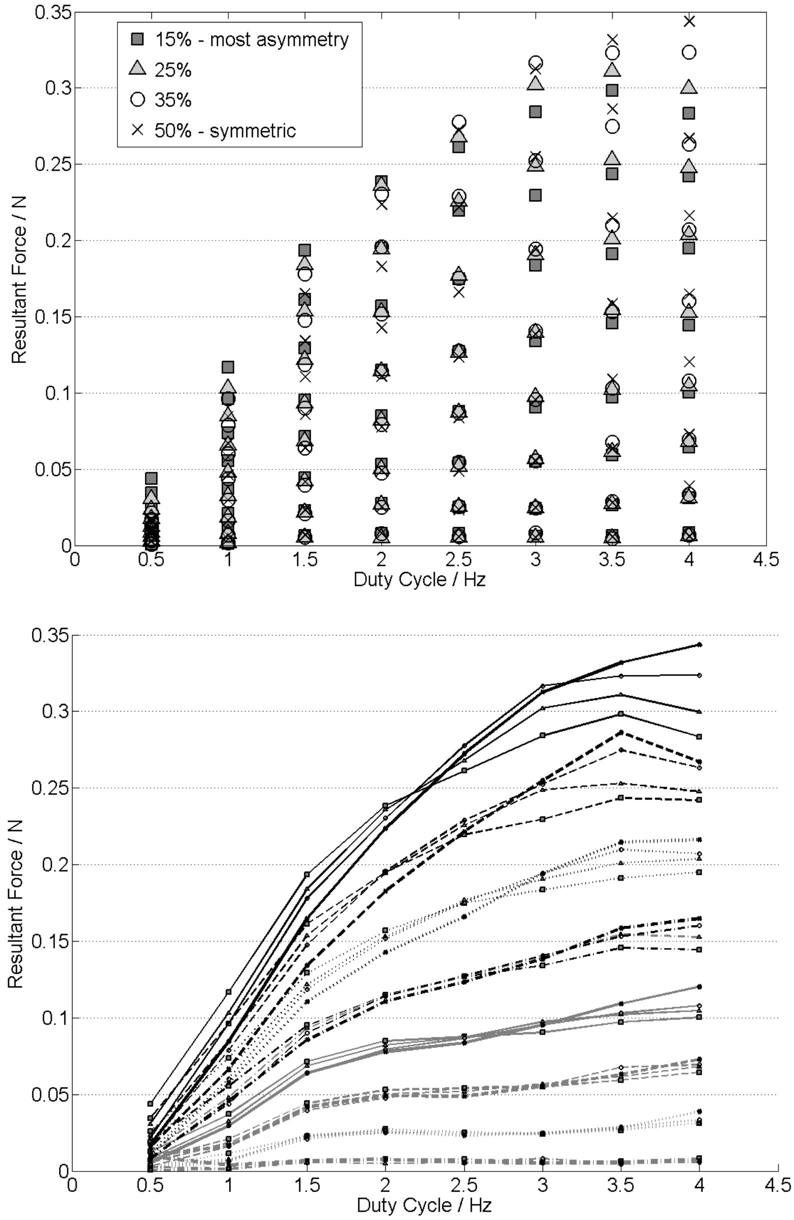
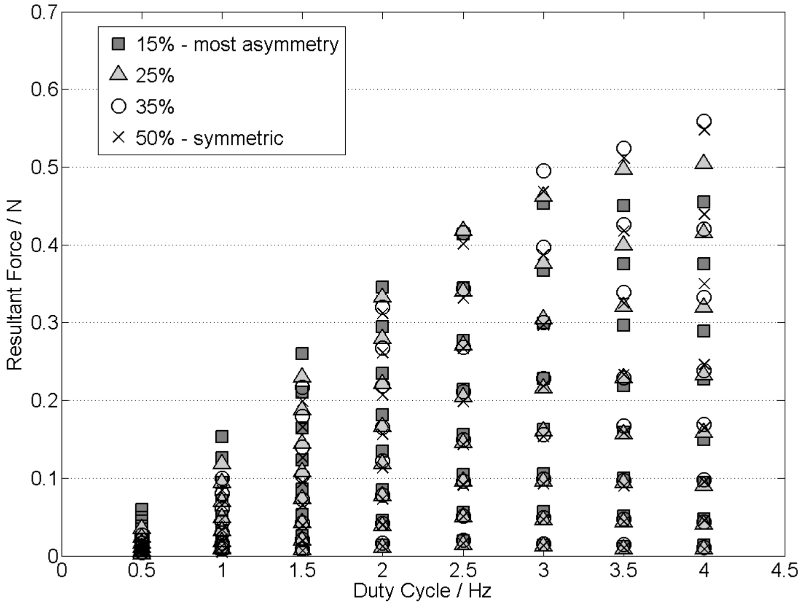


**Figure 3 – Force generation is shown for the less stiff 2D biomimetic fin for all angles. The percentages represent the time of the gross frequency that is given over to one half of the flap, thus 15% gives the most asymmetrical flap whereas the 50% flap is symmetrical. TOP: the data points for all angles arranged by asymmetry. BOTTOM: With the data points joined it is easier to rate the performance of each asymmetric profile. The line types represent the angular displacements with a heavier weight given to the symmetric profile. Solid black line, 16°, dashed black line, 14°, dotted black line, 12°, dash dot black line 10°, solid grey line, 8°, dashed grey line, 6°, dotted grey line, 4°, dash dot grey line, 2°.**



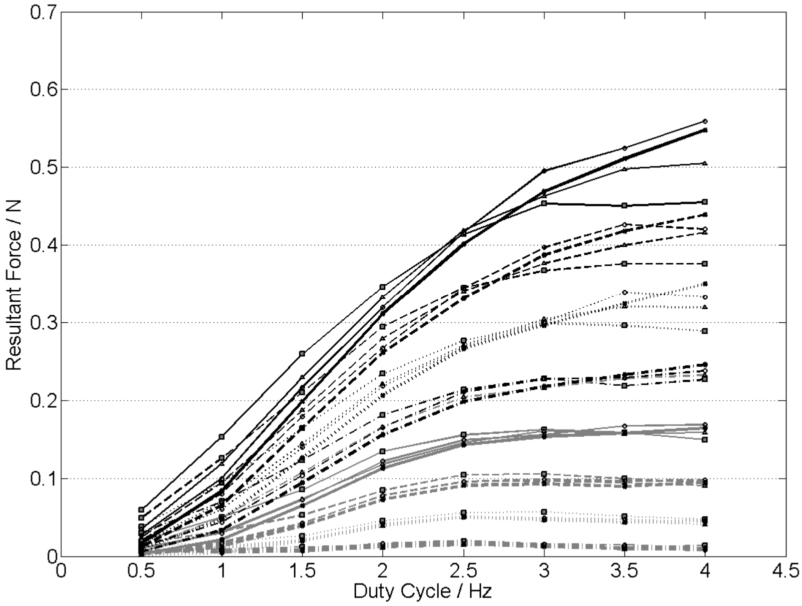


**Figure 4 – Force generation for the stiffer biomimetic fin. TOP: raw data points. BOTTOM: joined by lines based on the angular displacement - solid black line, 16°, dashed black line, 14°, dotted black line, 12°, dash dot black line 10°, solid grey line, 8°, dashed grey line, 6°, dotted grey line, 4°, dash dot grey line, 2°**

The overall trends described here are consistent for all fins and stiffnesses as seen in Figures 3 – 6, where the data points have been joined in the lower graph of each figure and the symmetric profile has been given a heavier line weight to allow easier comparison of performance. The force represented on the graphs is the total resultant force in the *x*-*y* plane, typically at an angle to the chordline of the fin at zero displacement. It is not yet possible to definitively describe how the resultant force angle changes as a function of the duty cycle frequency and angle but two trends appear. First, even the symmetric profile provokes a resultant angle (of around 20° for the less stiff NACA fin) and secondly, it appears that larger angular displacement provokes a larger resultant angle. These are tentative results and still need to be verified

### *A. Asymmetry is better at lower frequencies*

At low cycle frequencies (0 – 2 Hz) having a more asymmetric kinematic profile seems to improve force production for all fins at a given angle. Indeed, the profiles can be ranked from highest to lowest force

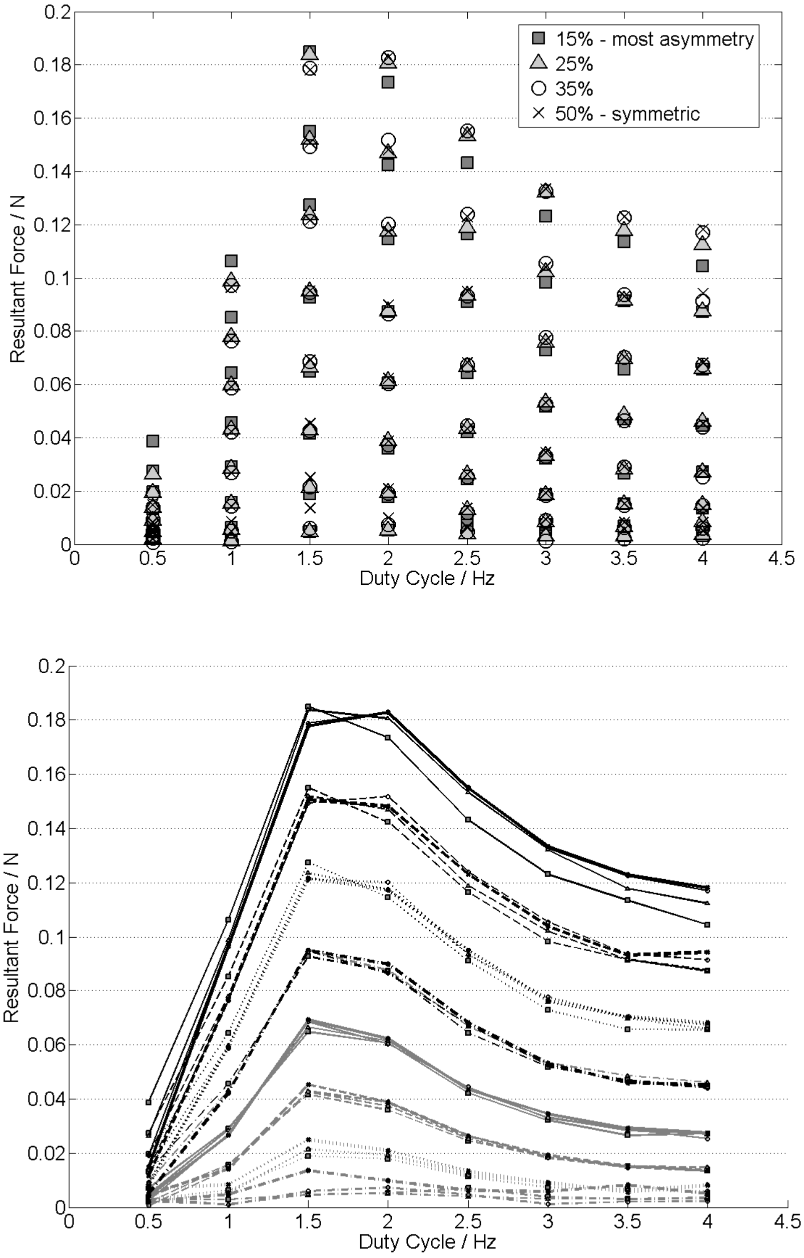


**Figure 5 – Force generation for the less stiff NACA fin. TOP: raw data points. BOTTOM: joined by lines based on the angular displacement - solid black line, 16°, dashed black line, 14°, dotted black line, 12°, dash dot black line 10°, solid grey line, 8°, dashed grey line, 6°, dotted grey line, 4°, dash dot grey line, 2°.**

producer as 15%, 25%, 35% and 50% or most to least asymmetrical. This is not the case at the higher frequencies investigated, where the symmetric profile generates the highest resultant force and the order of the profiles in terms of thrust production switches to least asymmetrical to most asymmetrical. This was found for all but the stiffer biomimetic fin (Figure 4), although this trend may hold true if the duty cycle frequency were increased. This is interesting since this is a good fit with the frequencies used by rays in normal swimming [1, 3], and kinematic asymmetry is a noticeable feature of some flapping rays' swimming.

### *B. Benefit of asymmetry is lost at different frequencies*

The transition of asymmetry from being beneficial to being detrimental occurs at a different duty cycle frequency depending on the physical properties of the fin: the stiffer the fin, the higher the transition frequency seems to be. For the other fins this transition occurs at different frequencies as described in Table 1.

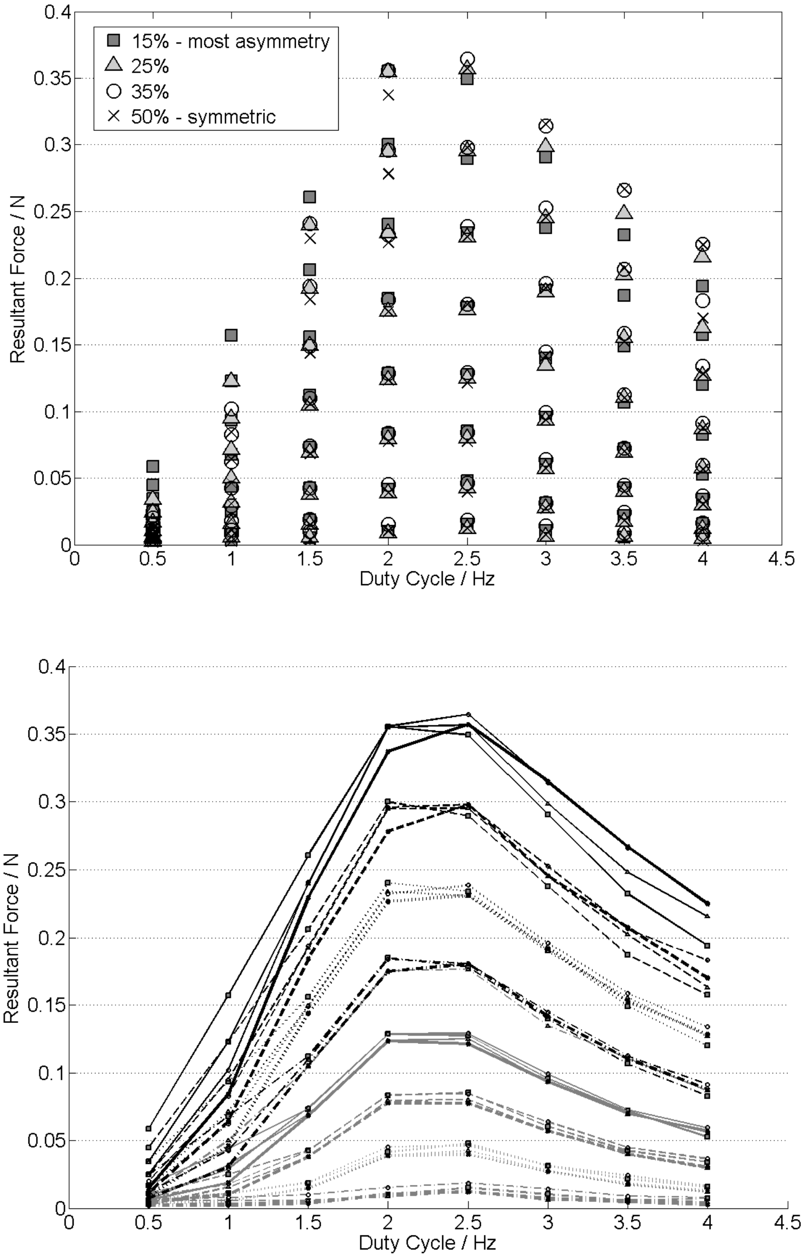


**Figure 6 – Force generation for the stiffer NACA fin. TOP: raw data points. BOTTOM: joined by lines based on the angular displacement - solid black line, 16°, dashed black line, 14°, dotted black line, 12°, dash dot black line 10°, solid grey line, 8°, dashed grey line, 6°, dotted grey line, 4°, dash dot grey line, 2°**

The angular displacement seems to play a role in the transition frequency but the actual relationship is not clear. For all but the lower stiffness NACA fin, a smaller angular displacement seems to increase the transition frequency of each kinematic profile. The values quoted in Table 1 are not the actual frequencies at which the transition occurs: they are the last recorded frequency at which there was a benefit. The way in which the data points are joined in the lower half of each figure gives a better idea of the actual value of duty cycle frequency at which this occurs. Further experiments with smaller frequency increments will help to clarify where the transition takes place. This is most likely a timing issue: the increase in, and subsequent loss of, resultant force is probably associated with vortex generation. Dabiri [5] has put forward that there is an optimal vortex formation time that is a better description of optimal propulsion than the Strouhal number, which is the more common classifier. The combination of gross stiffness, stiffness profile and kinematic profile will change the dynamic response of each fin in each condition and so change the time in which a vortex has to form. We hope to apply the vortex formation idea to this work and to see if this is a better indicator of force generation than duty cycle frequency. We also hope to show the fluid structures present with flow visualisation in further work.

| Angular displacement | Fin | NACA 2D | | Biomimetic 2D | |
|---|---|---|---|---|---|
| | | Stiff | Less stiff | Stiff | Less stiff |
| **16°** | **15%** | 2 | 1·5 | 2·5 | 2 |
| | **25%** | 2 | 1·5 | 2·5 | 2 |
| | **35%** | 2·5 | 2 | n/a | 3 |
| **8°** | **15%** | 2·5 | 1 | 3·5 | 2·5 |
| | **25%** | 3 | 0·5 | 3 | 3 |
| | **35%** | 3·5 | (1) | 4 | (3) |

**Table 1 – Transition frequencies (Hz): Each asymmetrical profile has a transition frequency at which it is no longer beneficial and this varies by the fin's physical properties. The transition frequency also depends on the angular displacement, though the relationship does not seem consistent across all fins. The brackets denote estimated values for series where the benefit of asymmetry is inconsistent.**

### *C. Benefit of asymmetry is lost at different rates*

The drop in force generation of the most asymmetrical (15%) profile in the biomimetic fins (Figure 3 and Figure 4) is greater, relatively, than the drop in performance of the same profile for the NACA profiles (e.g. Figure 5 and Figure 6). In addition, on the biomimetic fins, the drop rate is higher the more asymmetrical the flap profile but it seems to be consistent on the NACA fins.

### *D. Asymmetry benefit and fin type*

The percentage improvement that can be gained by using one of the asymmetric flapping profiles is higher on the stiffer fins than on the less stiff fins. This is slightly misleading as, here, the stiffness refers to the static material properties and does not include any effects of dynamic response or chordwise stiffness profile.

## V. CONCLUSIONS

Asymmetry has interesting effects on the force generation in flapping fins. The range and extent of its benefit is dependent on physical and kinematic parameters. First, asymmetry seems to benefit the lower but not the higher frequencies for both shapes of fin and both stiffnesses. Secondly, the transition from benefit to detriment of asymmetry depends on the physical properties of the fin (stiffer fins have a higher transition frequency) and the kinematic parameters of the flap profile (smaller angular displacements have higher transition frequencies up to a limit). These two phenomena can likely be linked to the time available for vortices to form in each experimental set up. It will be of benefit to verify whether vortex formation time is a better classifier of the data. Thirdly, the benefits of asymmetry seem to drop off more rapidly for the biomimetic fins than the NACA fins, with more asymmetry giving a faster drop off rate. Finally, the benefits of asymmetry are higher relatively for the stiffer fins, although this may also be better understood by looking at the vortex formation time.

## VI. ACKNOWLEDGEMENTS

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