Computational Investigation of Multiple Oscillating Hydrofoils and its Effect on Thrust Augmentation

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Abstract. Previous investigations of flapping hydrofoils for the purpose of thrust production have been limited to one or two in tandem. Tandem foils were found to have superior performance because the performance of the aft foil was augmented by the vortices shed from the fore foil. It is however not clear if increasing the number of foils will continue to have increased performance or if there exist an optimal number after which the overall performance either stagnates or reduces. A 2D computational study was conducted to investigate the effect of increasing the number of hydrofoils to four at a Reynolds number of 8000 flapping in-phase and out-of-phase. Optimal and sub-optimal conditions found previously with tandem hydrofoils were found also be applicable to three and four hydrofoils.

1 Introduction

Engineers have often looked to mother nature in order to get inspiration for improved solutions that are both simple and robust [1]. Bio-inspired studies and designs include flapping flight of insects and birds for micro air vehicle (MAV) applications [2]–[5] and the swimming of marine animals for undersea vehicles [5]–[9]. Traditionally aquatic vehicles such as submarines and ships have used propeller-driven propulsion utilising the rotation of propeller blades to create thrust. This form of propulsion although simple in design and efficient, has certain disadvantages such as cavitation when the angular velocity is sufficiently high, and are unsuitable for stealth operations. Unlike propeller driven propulsion, the dominant source of propulsion and manoeuvring forces found in marine animals is generated by flapping foils. For instance fish, dolphins and whales utilise the flapping caudal fins to efficiently produce large propulsive forces and swim gracefully and without any chaotic wake generated [10].

Important fluid dynamic features of swimmers and flyers in the animal kingdom are large motion amplitude and unsteady flow features. The fluid structure interaction between fluid and foil is highly complex as it includes the formation of large-scale vortex structures, onset of shear layer formation and subsequent reattachment and corresponding flow field. Previous studies [11], [12] have shown that flapping parameters such as: amplitudes of motion, phase difference between various components, and the Strouhal number (St) strongly affect propulsive effectiveness and efficiencies. Full 3D flapping motion is a combination of heaving, pitching and twisting motion however [2] suggests that significant thrust can be provided by pure oscillating (sometimes termed as pitching) 2D motion. Studies in oscillation of tandem foils (hydro or aero) have shown that under certain conditions, such as spacing and phase difference in the motion, the overall thrust performance can be improved beyond that of a single foil [13]–[15]. To the author’s knowledge, there has not been studies done beyond two foils to investigate if such performance augmentation continues and if they will stagnate or diminish beyond a certain number. The aim of this study is to investigate this using symmetric NACA0012 aerofoils.

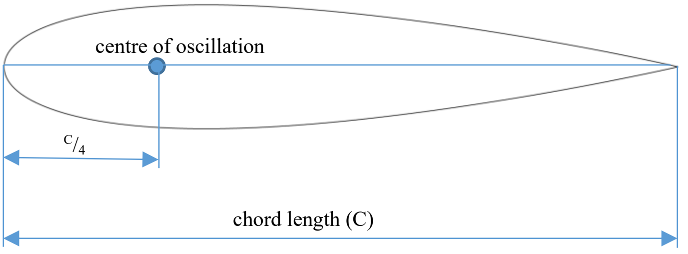
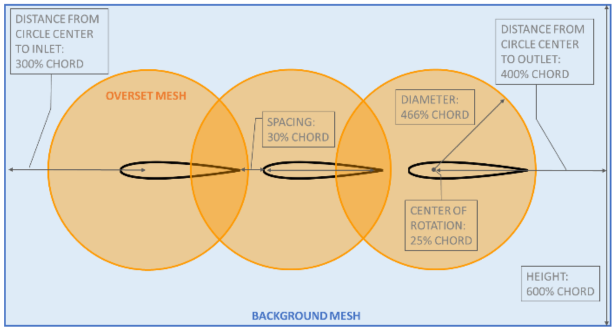


Figure 1: NACA0012 airfoil with quarter-chord located at the origin

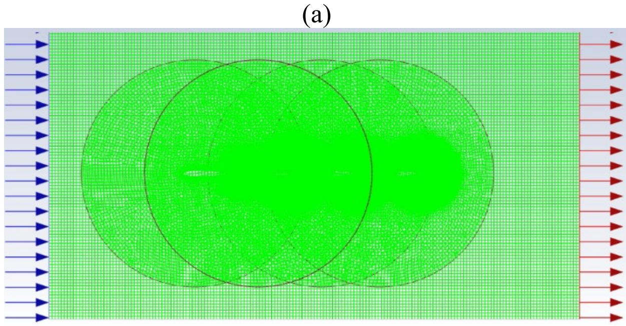
2 Methodology

Rigid two-dimensional foils undergoing oscillating motion was modelled using ANSYS Fluent to simulate the flow-field and to calculate the thrust (axially aligned with drag but in the opposite direction, hence negative of drag) subject to a constant horizontal flow of Reynolds number (Re) of 8000 based on the chord length of the airfoil and upstream flow.

The method utilised for the motion is the overset mesh which overcomes the limitations of using the simpler sliding mesh method whilst not requiring the large computational resources of the dynamic mesh method. Overset mesh method works by having two layers of mesh located one above the other. The layer which contains the foil (overset mesh) is smaller and is situated “above” the larger overall domain (background mesh). Information is passed between the meshes during solving. In scenarios with multiple foils, each foil is located in its own “overset” mesh and in certain locations, there are three “sets of mesh” overlapping in the same location. The flow domain consist of a rectangular background mesh with circular overset meshes as shown in Figure 2.



(a)



(b)

Figure 2:(a) Diagrammatic mesh setup (not to scale) (b)Representative mesh used in the simulations.

The solver settings used were double precision, pressure based, with the spacing between subsequent foils to be 30% of the chord length (0.3C). PRESTO! was used as the pressure discretisation scheme. The solution was first solved in steady-state without motion using the SST-kW turbulence model before switching to transient simulation using the Scaled-Adaptive Simulation (SAS) turbulence model. Simple harmonic pitching motion to the foil was prescribed using a user-defined function (UDF). Pseudo steady state was found to have been achieved after 5 cycles and all results presented are of the 6^{th} cycle.

Models with 1 to 4 foils were solved both in-phase and out-of-phase at a reduced frequency (k) of 1.26 Hz and oscillating amplitude of 20° giving a total of 6 sets of simulations. When multiple foils are out-of-phase, alternate foils will be in-phase, i.e. when there are 3 foils, the first and the third foils will be in-phase with the second foil out-of-phase by 180°. Similarly, when there are 4 foils, the first and third foils will be in-phase with each other while out of phase with the second and fourth foils. These two phase choices were made based on previous research which found in-phase to perform in an optimal manner while 180° out of phase performed in a sub-optimal manner for a spacing of 0.3C [15].

Several validation exercises were performed before a suitable mesh was selected. The first is the shape of the overset mesh. Validation was performed by replicating the settings and foil shape used by Flint et al [2] (via communication with the corresponding author of that paper) using a single foil due to availability of data. Although only thrust (negative drag) is required for this study, both lift and drag were used for the validation exercise.

First, an overset mesh using a circle the same size as that study was compared to an oval and ellipse was performed, and the result is shown in Figure 3. The circular overset mesh was eventually selected as it closely corresponded to the results by Flint et al [2].

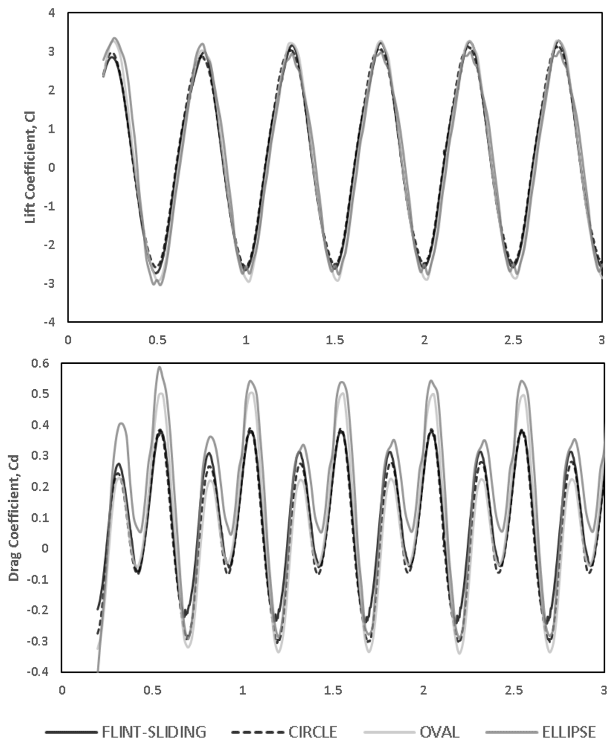


Figure 3: Comparison of overset mesh shapes.

The mesh sizing for the background mesh was refined to establish an appropriate mesh. The overset mesh utilised the settings by Flint et al [2] and is deemed to be suitable. Three background meshes termed "coarse", "medium" and "fine" were used and the results are presented in Tables 1 and 2 and Figure 3.

Table 1: Description of various background mesh tested.

Background Mesh	Description	Number of Nodes
Coarse	0.01m element size + face meshing, quadrilateral	7352
Medium	0.007m element size + face meshing, quadrilateral	14679
Fine	0.005m element size + face meshing, quadrilateral	28741

Table 2: Comparison of results from different meshes.

	Cl Difference			Cd Difference		
	max	average	average %	max	average	average %
Coarse	0.062	-0.008	0.606	0.017	0.00167	0.287
Medium	0.127	-0.009	-0.875	0.023	0.00221	0.423
Fine	0.061	-0.007	0.542	0.017	0.00122	-0.175

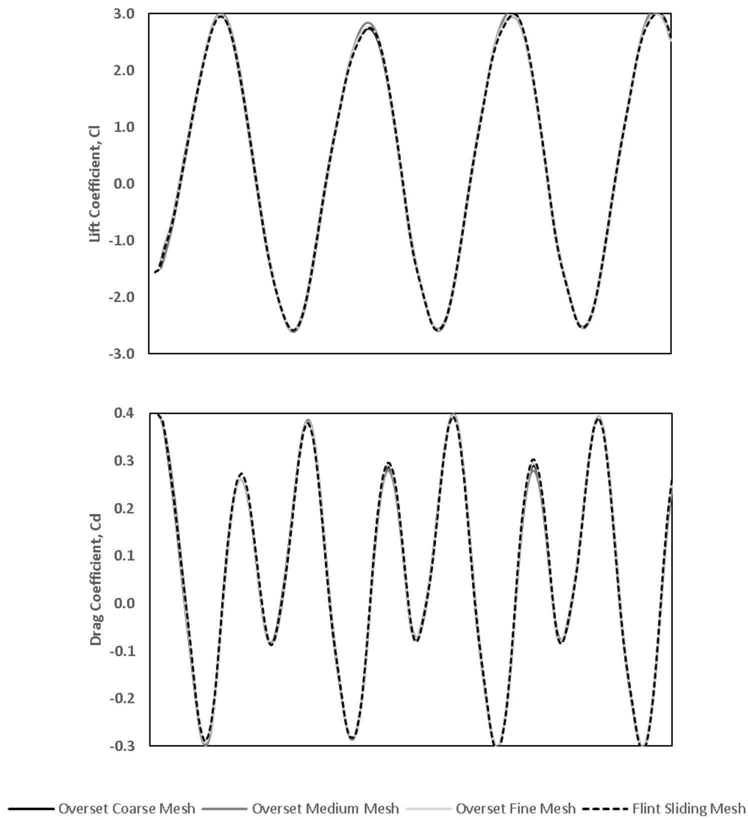


Figure 4: Graphical comparison of results from different meshes with respect to time

The solver settings used were double precision, pressure based, with the spacing between subsequent foils to be 30% of the chord length (0.3C). PRESTO! was used as the pressure discretisation scheme. The solution was first solved in steady-state without motion using the SST-kW turbulence model before switching to transient simulation using the Scaled-Adaptive Simulation (SAS) turbulence model. Motion was prescribed using a user-defined function (UDF). Pseudo steady state was found to have been achieved after 5 cycles and all results presented are of the 6th cycle.

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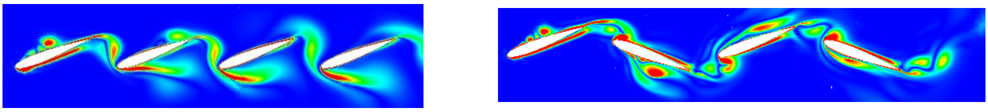
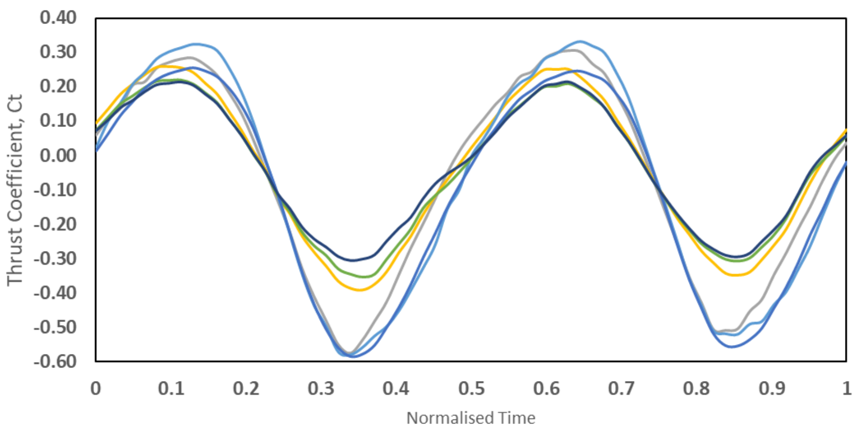


(a) (b)

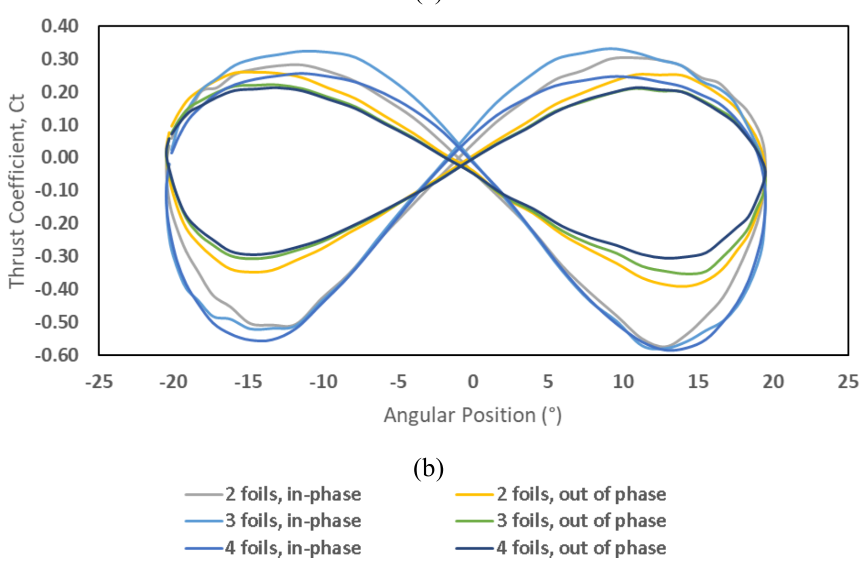
Figure 5: Illustration of (a) foil motions being in-phase and (b) foil motions being out-of-phase

3 Results and discussion

First it can be observed from Figure 6 that for all the scenarios, the drag coefficients against time and oscillation pitch angle show the expected trends. What is presented is only the net thrust produced by the entire system, but the individual foils exhibit similar behaviour and are omitted for the sake of brevity.



(a)



(b)

Figure 6: Thrust coefficient (a) against time and pitch angle (b) for systems with multiple foils.

Net thrust coefficient generated by the foil systems is given in Figure 7. An immediate observation of note is that within the conditions simulated, there was no net thrust generated. St in the current study is 0.21. The comparison between the current study and previous results are given in Figure 8. Since the Strouhal number is inversely proportional to the speed of the oncoming flow, a decrease in flow speed would increase the Strouhal number, potentially enhancing the net thrust. This is further supported by the fact that the thrust was unable to overcome the drag produced by the system. A system with slower oncoming flow would also experience less drag.

It is interesting to note that the out-of-phase scenario generated more thrust for the two and four foil system but there is a switch-over at three foils. For foils oscillating out of phase, there is drop in net thrust with three foils, but it increases again for four foils. It is not clear if the increase will continue beyond four foils.

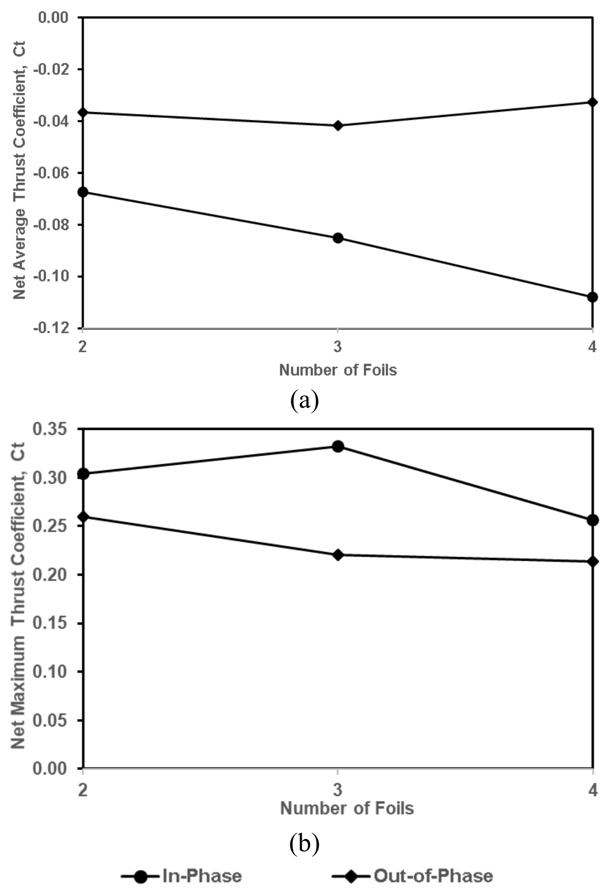


Figure 7: (a) Net average thrust coefficients and (b) net peak thrust against number of foils

When two or more foils are pitching in tandem, the wake of the fore foil affects the flow around and hence the performance of the aft foil. The vortices shed by the fore foil interact with those being formed on the aft foil and, for this spacing, for a 0° phase difference these interact constructively and are hence rotating in the same direction while for a 180° phase difference these act destructively and can be observed to be rotating in opposite directions. The observation of a phase difference of 0° being optimal and 180° being suboptimal for thrust performance for two tandem foils is found to hold true for systems of three and four foils when considering the net maximum thrust coefficient of the system. The destructive effects of the suboptimal cases became less devastating to the last foil as more foils were placed between the first and last foils. This is evident in the flattening of the trend between the three and four foil system net maximum thrust coefficient as well as the upward trend for the net average thrust coefficient for out of phase cases seen in Figure 5. In such cases, it has been observed that the effects of vortex interaction on the last foil decreases with the number of foils. When vortices are formed and shed, energy is extracted from the flow to be converted into a rotational velocity of the fluid elements. As more energy is extracted from the flow, less energy is available for additional vortices to be formed and shed hence reducing the significance of vortex interaction by reducing the strength of the vortices involved.

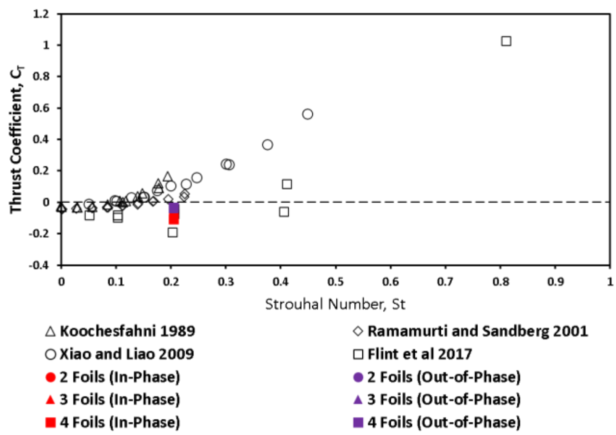
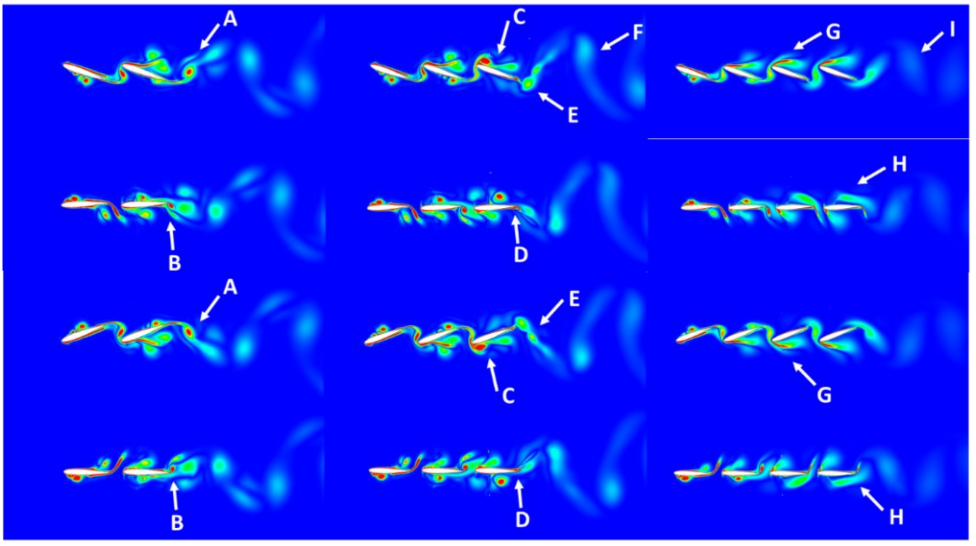


Figure 8: Comparison of current results against literature

To elucidate the results mentioned above, one needs to study the shedding of vortices during the motion. First, we compare the results between the case of two, three and four foils for the 20° amplitude motion.

During in-phase motion, the vortex shed off the second foil in a two-foil system (A) in Figure 7 is what develops into the strong leading-edge vortex (LEV) on the third foil of a three-foil system (C). The interaction between the first and second foils is similar for both two-foil and three-foil systems. This is, however, not the case for the four-foil system whose only similarity is in the vortex structures formed on the fore foil. This system has a more sheet-like interaction pattern between the second, third and fourth foils (H). It is interesting to note that there is far more roll-up of the shed sheet vortex at the midway amplitude of the two-foil system (B) than of the third foil of a three-foil system (D). This progressively becomes more sheet-like in the four-foil system (H).

An interesting thrust performance enhancing mechanism was discovered on the drag performance of the third foil resulting in a 68% increase in peak thrust (peak) without a significant increase in peak drag (trough) in Figure 6. This foil experienced a “double hump” peak which were also observed in the two previous studies [2], [16] but was not extensively explained. This increase could be attributed to the LEV formation being enhanced by the constructive interference of the vortex sheet rollup of the foil fore of it as shown in Figure 7(C). This phenomenon was not present on the third foil in the equivalent case of four foils wherein the sheet shed off the second foil experiences little to no rollup in its interaction with the leading edge of the fourth foil. A possible reason for the "double hump" could be linked to the double vortices being shed (E) which differ from those shed from the two-foil system (A). Another visual indicator in the difference between thrust performance of the three and four foil systems is the size and strength of the wake aft of the system: the wake of the three-foil system (F) occupies a wider area and has a higher vorticity than that of the four-foil system (I).



Two foil system Three foil system Four foil system

Figure 9: Vorticity contours for in-phase

During the out of phase motion, the vortex sheet shed off the fore foil of a two-foil system destructively interferes with the leading-edge vortex being formed on the aft foil (J) to produce an overall smaller leading-edge vortex (K). Contrasted to the in-phase motion, the vortex structure on the second foil (L) does not differ between two and four-foil systems. The interaction between the first and second foil (J) is also unchanged (N). For the four-foil system, the trailing edge vortex rollup of the third and fourth foils (M) has lower vorticity than the that of the second foil (N). The wake produced in the out of phase motion (O) occupies a smaller area and has a lower vorticity than that of the in-phase motion (I) and is shaped in more discrete clusters (O) rather than a continuous swirl (I). The difference of the wake is once again a visual indicator of difference in the thrust being extracted from the flow.

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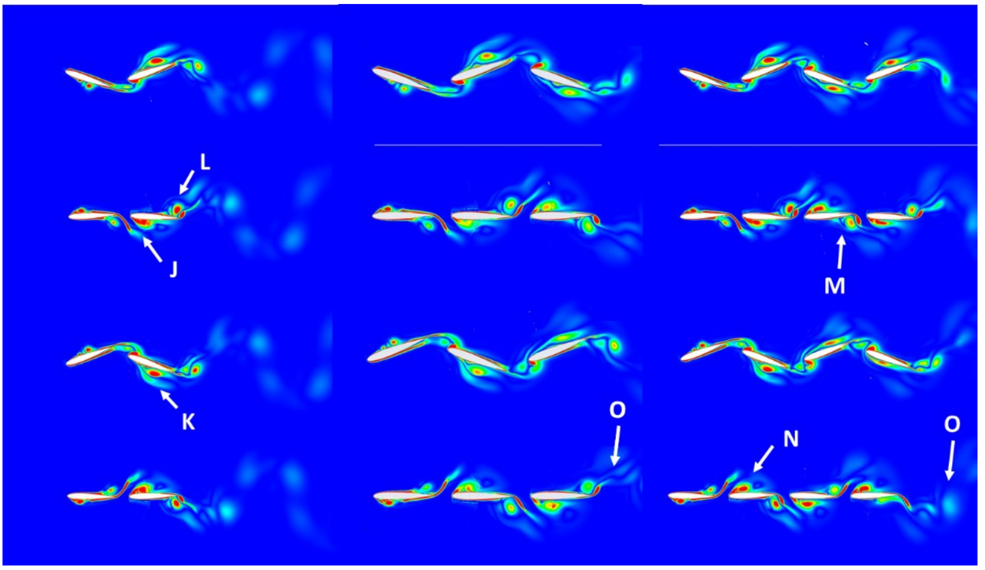

Two foil system

Three foil system

Four foil system

Figure 10: Vorticity contours for out of phase

4 Conclusion

A study has been performed on the thrust capabilities of symmetrical hydrofoils undergoing harmonic oscillating motion under different operating conditions. The Reynolds number, Strouhal number and reduced frequency of the simulations were 8000, 0.21 and 1.26 respectively. Known optimal and suboptimal conditions for tandem flapping double foil cases were tested for triple and quadruple tandem foil sets. These were found to have a similar effect on the enhancement or diminution of performance of triple and quadruple foil cases. There was no further system performance enhancement found after three foils and the addition of a fifth foil was not studied on the basis of this trend. The system was unable to produce a net positive thrust for all cases tested likely attributed to the incoming flow velocity being too great and resultantly inducing too much drag. Future work could investigate the effects of increasing spacing or the possibility of combined pitching-heaving motion to improve thrust performance by means of introducing an additional velocity component.

References

[1] J. C. Nawroth et al., Nat. Biotechnol., vol. 30, no. 8, pp. 792–797, (2012)

[2] T. J. Flint, M. Jermy, T. H. New, and W. H. Ho, Int. J. Heat Fluid Flow, vol. 65, pp. 328–341, (2017)

[3] N. M. Shumway, M. Gabryszuk, and S. J. Laurence, AIAA Aerospace Sciences Meeting, 2018, no. 210059 (2018)

[4] Y. H. Chen and M. Skote, Phys. Fluids, vol. 27, no. 3, (2015)

[5] H. Hu, L. Clemons, and H. Igarashi, Exp. Fluids, no. 51, pp. 347–359, (2011)

[6] A. H. Techet, J. Exp. Biol., vol. 211, no. Pt 2, pp. 274–279, (2008)

[7] F. E. Fish, P. W. Weber, M. M. Murray, and L. E. Howle, Integr. Comp. Biol., vol. 51, no. 1, pp. 203–213, (2011)

[8] F. E. Fish, Appl. Bionics Biomech., vol. 3, no. 1, pp. 49–60, Jan. (2006)

[9] H. Liu, Appl. Mech. Rev., vol. 58, no. 4, pp. 269–282, (2005)

[10] C. L. Yu, Y. H. Hsu, and J. T. Yang, Ocean Eng., vol. 70, pp. 51–60, (2013)

[11] D. A. Read and M. S. Triantafyllou, p. 153, (2001)

[12] F. S. Hover, Haugsdal, and M. S. Triantafyllou, J. Fluids Struct., vol. 19, no. 1, pp. 37–47, (2004)

[13] K. B. Lua, H. Lu, X. H. Zhang, T. T. Lim, and K. S. Yeo, Phys. Fluids, vol. 28, no. 12, (2016)

[14] L. E. Muscutt, G. D. Weymouth, and B. Ganapathisubramani, J. Fluid Mech., vol. 827, pp. 484–505, (2017)

[15] T. M. Broering and Y.-S. Lian, Acta Mech. Sin., vol. 28, no. 6, pp. 1557–1571, (2012)

[16] Y. Shen and H. Cai, J. Vibroengineering, vol. 18, no. 3, pp. 1839–1848, (2016)