Geometric Investigation of Tandem Flapping Hydrofoils Under Wave Orbital Motion

Aarav Joshi

Received September 21, 2022
Accepted February 07, 2024
Electronic access March 15, 2024

The field of hydrodynamics propulsion is critical in reducing carbon emission and mitigating the effects of climate change. In this study, we investigate a propulsion technique that involves two free-flapping hydrofoils arranged in tandem configuration which make use of wave orbital motion to generate vessel forward thrust. This system does not require any input energy and can have numerous applications such as propelling autonomous surface vehicles, which are fundamental for mapping ocean currents, gathering climate data, etc. In this paper, we make use of computational fluid dynamics (CFD) to investigate the impact of hydrofoil shape in a tandem flapping foil configuration which converts wave energy into thrust. Given a fixed inter-foil spacing and environmental parameters, we account for wave orbital motion, vessel forward motion, and wake effects.These are the major factors that affect the system's overall thrust output while also accounting for system efficiency. Through this study, we hope to increase the propulsion system's overall functionality, and facilitate the system's integration across a wider range of vessels. The study also satisfies the goal of determining the optimal configuration of different thickness to chord ratio over both hydrofoils, which has been an unanswered question on the propulsion system. Through the testing of different thickness-to-chord ratios we revealed that the configuration with the thicker forward foil, characterised by a higher velocity deficit and vorticity, thereby reducing the efficiency of the aft foil. However, the gain in thrust that is provided by the forward foil is enough to produce a net higher total thrust over a system with identical foils on both positions.

Keywords: Flapping Foils, Flapping Hydrofoils, Tandem Foil Configuration, Thrust Generation, Wave Orbital Motion, Wake Interaction, Foil Shape.

Introduction

Nature has always inspired scientists and aided them in designing many of the machines we use today in our daily lives. The field of hydrodynamics is no different. Especially in the field of vessel propulsion, aquatic animals over millions of years of evolution have developed very efficient propulsion techniques. One of these propulsion methods uses flapping foils in a tandem configuration, which can be compared to pectoral flippers of marine turtle and penguin species, or to fish moving against currents in rivers or in the trail, also referred to as wake, of other fish. The propulsion method being investigated in this study consists of a tandem flapping foil configuration, hence a forward and an aft foil setup that moves and rotates about the vertical and transverse axis, respectively. The main idea is to extract energy from wave orbital motion, which refers to the movement of particles or objects in a wave as they undergo circular or elliptical paths. As these foils move and rotate, they extract energy from the wave motion and create a positive force in the forward direction, referred to as thrust. This technology has numerous applications. Its main one is providing the propulsion system for small Unmanned Surface Vessels (USV), which are used to collect vast amounts of scientific data on a large scale. Such vessels have been in testing but the technology has never seen any significant use on even a minor scale. Furthermore, this method of propulsion does not depend on any fossil fuels or electricity making it a very environmentally and economically friendly propulsion technique. Our research is focused on Investigating and optimising this system to increase its efficiency, allowing a larger use of this technology and a stronger benefit to the environment, aiding humanities strive to become a carbon neutral civilisation. We hope our simulations can be used by any feature companies looking to use this technology for USV's, to make their vessel overall more efficient. Over the years, such a propulsion system has been investigated by many researchers, which contributed to the current stage of this technology.

Studies conducted by Knoller and Betz[1] were among the first to investigate the lift production of flapping foils in a uniform flow. These findings are referred to as the Knoller-Betz effect and were further investigated experimentally by Katzmayr[2] which proved the possibility of generating positive thrust. However, the experimental setup involved an incoming flow to be uniform thus reducing the accuracy and they only used a single foil which meant no wake interactions were tested. Taking inspiration from fish tails and fins, Akhtar[3], conducted research on the possibility of having a two-foil, i.e., tandem, configuration. Findings indicate that the presence of an upstream flapping foil can, in some conditions, increase the generated thrust of the aft foil due to the exploitation of the shedding vortices generated by the forward foil. However, this phenomenon is highly dependent on inter-foil spacing. The investigation however did not consider the impact of the three-dimensional foil shape, hence neglecting three-dimensional flow effects that can impact the final generated thrust. The study also did not make use of wave orbital motion and how it interacts with the tandem foils. Tandem flapping foil configuration was further investigated by L. E. Muscutt[4] who conducted two-dimensional numerical simulations on the addition of an aft foil. He stated that using two foils can lead to some distinct efficiency advantages over a single foil system, showing almost twice the efficiency for the investigated conditions. Moreover, Muscutt[4] also concluded that the best motion combination for the flapping foils is with a phase lag. This reduces the impact of the forward foil wakes onto the aft foil. However, the accurate prediction of the forward foil wake and its impact on the aft foil performance still remained an area of concern for a tandem flapping foil configuration. To address this, Penglei[5], conducted research on the difference in energy harvesting capability of two tandem flapping foil configurations. The first one consisted of the foils being arranged in parallel, i.e. without any wake-foil interaction. The second is an inline setup, involving a forward and an aft foil, where the forward foil generated wake interacts with the aft foil. The study showed that, in a uniform inflow, the parallel foil configuration could exhibit a lower energy harvesting efficiency than the inline one for certain conditions. Post this discovery a greater focus was shifted to wake interaction in this system to make it more efficient. Forward foil wake generation and wake-foil interactions in tandem flapping foil configurations were then further investigated by B.Ribeiro[6] who investigated the wake structure in a tandem foil system and its correlation with the foil kinematics by conducting both numerical and experimental campaigns. The study showed the efficiency of the aft foil to be a function of the inter-foil spacing and inter-foil phase angle. None of the studies mentioned above account for wave motion, vessel motion, and foil-wake effects simultaneously. This is addressed by Chipolina[7], where the impact of inter-foil spacing on the foil system efficiency was investigated with two Computational Fluid Dynamics (CFD) numerical methods: potential flow theory and Raynold Averaged Navier Stokes (RANS) simulations.

The aim of this study is to address the impact of the shape of the forward foil in a tandem flapping foil configuration when wave motion, vessel motion, and foil-wake effects are all considered. We also look to test our hypothesis that the system with the thicker forward foil will have the greatest total thrust production over a full cycle. By using the RANS simulation software STARCCM+[8], 2D simulations of various combinations of foil thickness to chord ratio are investigated in terms of forward propulsion efficiency.

The remainder of the paper is organised as follows. Section 2 will describe the investigated flow and kinematics conditions, foil geometry, and introduce the CFD solver STARCCM+[8]. Section 3 will present the main findings with the related discussion. Finally, Section 4 will address the main conclusions and specify future work.

Methodology

All the above-mentioned studies take into account, often individually, different aspects of the investigated propulsion system. For instance, these include wave orbital motion, inter-foil spacing, the effect of the forward wake on the aft foil, etc. However, the shape of the forward hydrofoil section and its impact on efficiency have not been studied with the combination of wave orbital motion, the effect of forward foil wake, and vessel motion. The goal of our study is to fill this void and bridge this gap. This shall be accomplished using computational fluid dynamics, in particular the commercial software STARCCM+[8], which solves the Reynolds-Averaged Navier Stokes (RANS) equation. Three different forward foil thickness to chord ratios are investigated to determine the impact on its thrust production and the effect of the generated wave onto the aft foil.

This segment addresses and establishes the core issue at hand. In this section, we present and elucidate the primary governing factors. These encompass environmental conditions, kinematic aspects, and performance criteria. Subsequently, we organise our central dimensionless constants. Following this, hydrofoil geometry is introduced, specifically outlining the hydrofoils we intend to examine. This description is supplemented by an elucidation of the NACA-4 digit system. The subsequent portion of the paper delves extensively into the CFD solver used, STARCCM+[8], which will be instrumental in generating our simulated dataset.

Problem Setup

The propulsion system consisting of a tandem flapping foil configuration does not involve the use of any powered components. This poses environmental and geometrical parameters as key aspects in the ability of the system to generate vessel forward motion, hence thrust. In this study, we replicate the conditions defined in Chipolina[7] as suited for a USV and for which there is experimental data available. As a general overview, we consider a vessel of length 2.27m and a pair of flapping foils of chord 0.23m (refer to the next section for more hydrofoil geometry details) operating in water at a distance of 50% of the vessel LWL. This spacing is chosen to achieve wake-foil interaction, providing insight into the impact of forward foil shape and wake generation. A schematic diagram of the 2D problem is presented in Figure-01, while the main particulars of the setup are provided in Table.2.

The Diagram above (Fig.1) depicts the tandem configuration that is being tested here. As we can see the wave orbital motion first comes into contact with the forward foil at an angle of attack [a1(t)]. By this interaction, and by the free movement of the forward foil the foil generates thrust. However as can be seen in Fig.1 the forward foil also leaves wake (turbulent flow) behind it which then hurts the final thrust production of the aft foil as the flow it is interacting with is not in the most ideal condition.

Regarding environmental factors, the first key parameter to define is inflow speed and direction. The inflow velocity can be defined as the velocity of the incoming fluid, and it is a critical parameter because it directly affects the behaviour of tandem flapping foils. The flow velocity vector, i.e., magnitude and direction, determines the relative speed and the angle between the foils and the fluid, which directly impacts lift, the hydrofoil force component generated perpendicular to the incoming flow; drag, force component parallel to the inflow direction; and thrust, which is the force component in the forward direction, hence a good indicator of the overall vessel performance. In this study, we relate the inflow velocity vector to wave orbital motion and the vessel motion itself. Given a wave frequency ω and a wave-induced velocity u_0, we define the velocity components as:

$$u_{0x} = u_0 \sin(\omega t + \phi) - u_{\text{Vessel}},$$

$$u_{0y} = u_0 \cos(\omega t + \phi),$$

where u_{Vessel} is the forward speed of the vessel and ϕ represents the phase shift with the forward foil motion, set to 2π to achieve higher thrust as specified in Chipolina[7]. Other environmental parameters are the dynamic viscosity μ, and the density ρ. The latter is held constant due to operations at a low Mach number. Hence we can assume the flow to be incompressible.

Moreover, there are also various non-dimensional numbers that play a critical role in understanding flow behaviour and the different aspects of fluid flow. These parameters are particularly relevant in analysing the flow around objects such as foils and their impact on lift generation, drag, and overall flow behaviour. The first is the Reynolds number, $Re = \frac{\rho c U}{\mu}$, where c is the foil chord length and U is the incoming flow velocity magnitude. It defines the flow behaviour and characteristics, which are calculated based on fluid velocity and density. Reynolds number also determines the flow regime, with a high Reynolds number leading to turbulent flow and a low Reynolds number signifying laminar flow. In our case, the Reynolds number is within the transition and turbulent region, especially given the relatively high angles of attack of the hydrofoils.

In terms of foil flapping motion, we prescribe heaving and pitching to the aft and forward foil following the experimental results mentioned in Chipolina[7]. Pitching and heaving motions are defined as

$$\alpha = \alpha_0 \cos(\omega t + \phi),$$

$$A = A_0 \cos(\omega t + \phi),$$

where α_0 is the pitching amplitude, A_0 the heaving amplitude, ω the wave frequency, and ϕ the aft foil phase shift ($\phi = \pi$).

While all the above-mentioned factors are very important, there is a need to quantify and compare the foil configurations to study their impact on the system. This is where performance parameters come in. These performance parameters provide proper quantitative ways for evaluating and comparing different flapping foils in different conditions and parameters, studying the effects of various design factors, optimizing performance, and producing conclusive results. To be able to provide a quantitative comparison, the main performance parameter we are using is thrust. Thrust can be looked at as the push and pull acting on a system. In simpler terms, it is the force that propels a body forward or backward. Thrust in the system of tandem free-flapping foils can be derived from the lift and drag components, and its coefficient is expressed by

$$C_t = \frac{T}{0.5 \rho U^2 c}$$

Due to the main aim of this propulsion system being a forward force to the vessel as efficiently as possible, thrust is chosen to be the most appropriate parameter to quantify propulsive efficiency and draw conclusions from our investigation.

Hydrofoil Geometry

Geometric parameters are the main parameters defining the geometry of the hydrofoil. These are vital when designing and analysing flapping foils. Changing these parameters allows researchers to get an insight into their impact on the lift, drag, and other performance metrics. The reason for studying the geometric factors is to understand the influence of geometric parameters and aid in optimising foil design for other applications or performance objectives.

As shown in Fig.2, the leading and trailing edges are defined as the points at which the fluid first enters in contact with the foil surface and last leaves it, respectively. The distance between these two points is called the chord, while the asymmetry of the shape is determined by the camber. No camber implies a symmetric foil section, while the presence of camber determines an asymmetry one. The exact shape of the foil is expressed in terms of the thickness and camber distribution, which determine the distribution of pressure and influence lift and generation, as well as vorticity, flow regime, and flow separation. In this study, we consider the symmetric NACA 4-digit foil shape, and we investigate the impact of the thickness-to-chord ratio on the

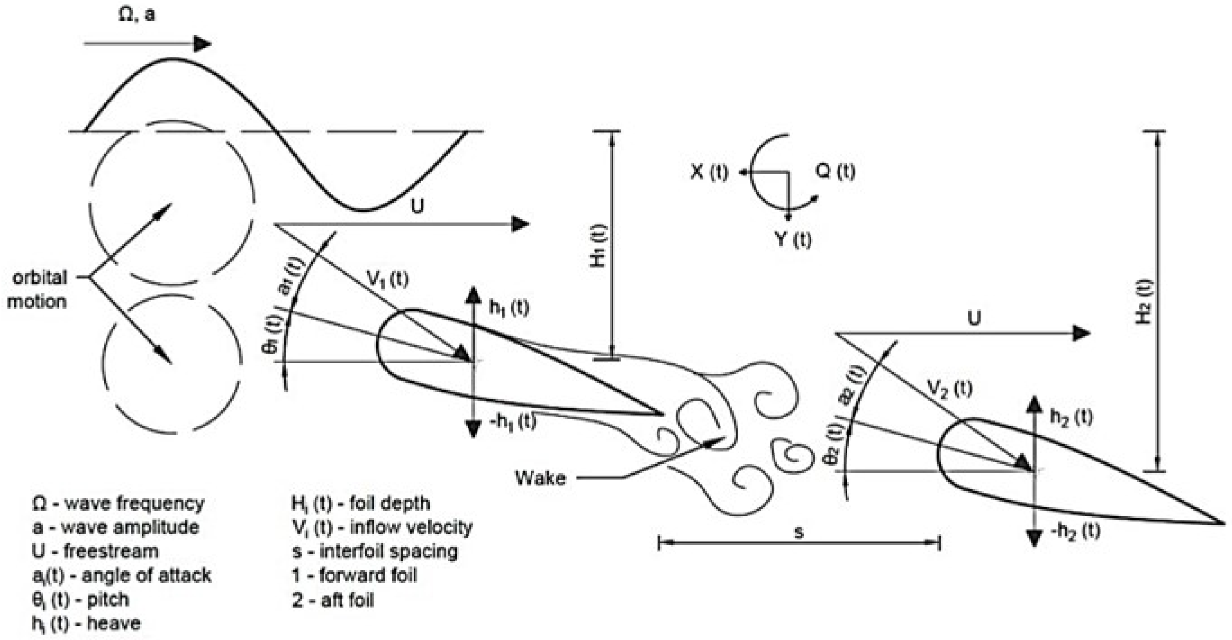


Fig. 1 Diagram representing the investigated problem, where pitching and heaving hydrofoils are subject to incoming wave orbital motion. Also seen in the picture is the wake that is generated by the forward foil. Chipolina[7].

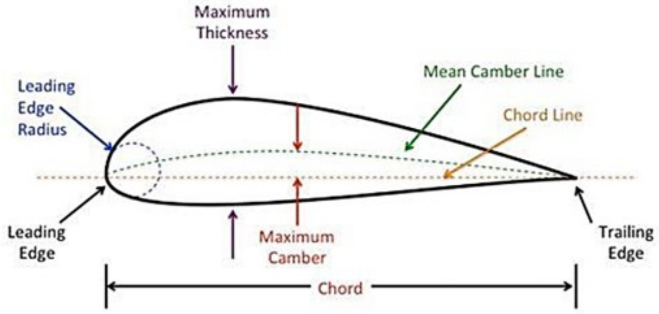


Fig. 2 Main geometric parameters defining a foil section. Anderson[9]

Configuration No.	Forward Foil	Aft Foil
Configuration 1	NACA-0008	NACA-0012
Configuration 2	NACA-0012	NACA-0012
Configuration 3	NACA-0015	NACA-0012

Table 1 Tested combinations of sections for forward and aft hydrofoils.

propulsion efficiency. The aft foil geometry is fixed to a NACA-0012, while we will be testing 3 different foil shapes for the forward foil More specifically, a NACA-0008, a NACA-0012, and a NACA-0015. A summary of the three configurations tested is presented in Table.1. To further understand the foil shapes as they are the main variable in our study it is important to understand the NACA-4-digit system. The first digit describes maximum camber length as a percentage of the chord. As we can see in Fig.2 the camber line (blue dotted line) describes the bend in a foil. The more the camber line deviates from the chord line, the more asymmetric the foil shape is. However, in a flapping foil system, both surfaces are needed to generate thrust as the pitch motion is periodic. Hence we use symmetrical hydrofoils in which the camber line coincides with the chord line itself. This is indicated by the first being 0 in the NACA 4-digit notation. The last two digits describe the maximum thickness of the foil as a percentage of the chord.

Computational Fluid Dynamics Solver

In this study, we utilise the commercial software STARCCM+[8], which consists of a finite volume solver for the RANS equations in an unstructured mesh. The $k\omega-$SST turbulence model is used, as well as a segregated solver for the implicit unsteady formulation of the problem. In terms of validation, the obtained values for lift, drag, and thrust are compared with the ones presented in Chipolina[7], yielding great similarities. All the simulations were conducted on a Dell G3 integrated with the NVIDIA GeForce GTX 1660 Ti Graphics Card. A limitation regarding the software choice was that we are only testing 2D configuration with this software. However, in 3D there are some extra vortices that start generating whose effects are not nonsignificant on the wake. This can therefore introduce some error in the overall simulations however old experimental data shows we can still get quite accurate data and results without taking it into account.

The following particulars were set for all simulations while changing only the foil configurations in order to produce comparable data. The particulars set for the simulations are the same as were taken in Chipolina[7] as they have been taken from experimental data and are therefore the closest representation of the real world possible.

Results

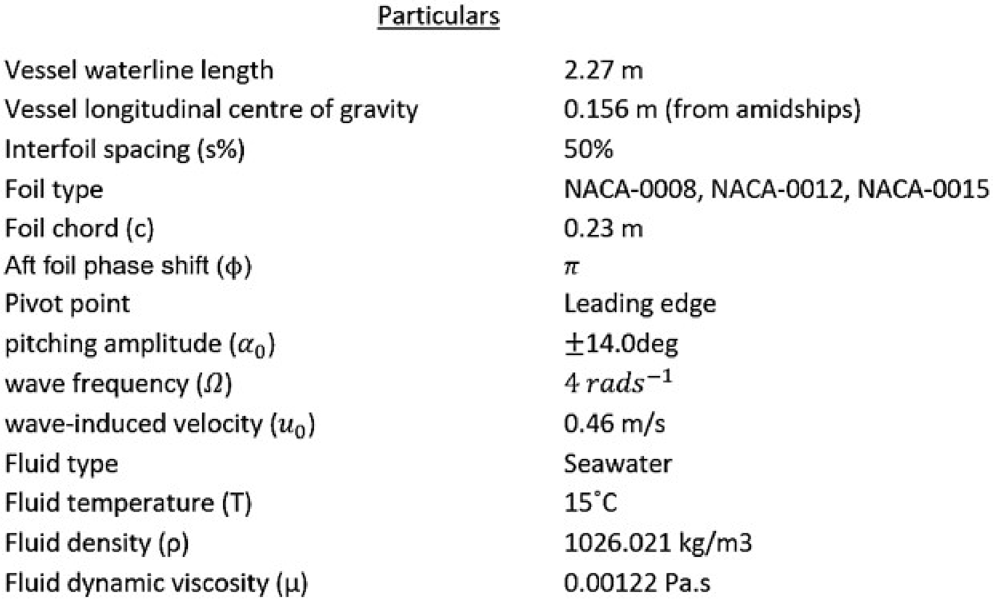
This section presents the results and discussion for the simulated flapping foil configurations. The presented findings include qualitative and quantitative comparisons with the aim of determining the most efficient configuration and assessing the physical reasons behind these findings. The main criteria investigated are the thrust coefficient, as well as velocity and vorticity fields. As a reminder for the reader, in the three configurations assessed, the forward foil thickness to chord ratio is varied while keeping the aft foil one is held constant as specified above in Table.2.

Having a condition where the frequency of motion of the foils corresponds to the frequency of the incoming waves, we present the results in terms of cycle time for a single cycle of motion, i.e. time normalised by the foil motion period. Thrust coefficient results are provided since the goal of the system is to provide propulsion, implying the highest total thrust coefficient (Ct) corresponds to the highest efficiency. In Fig.3 and Fig.4, the forward foil and total thrust coefficients, respectively, are shown for the three different configurations: C1, C2, and C3 (refer to Table.1.). Some key differences between the configurations can be observed. In terms of the forward foil thrust coefficient (Fig.3), we can observe that, as expected, a thicker foil overall produces a higher thrust. When considering the total thrust, hence including the impact of the forward foil onto the overall system, we notice that, apart from a region around 3.6 cycles, a thicker forward foil configuration still generates a significantly higher thrust. To verify this, Fig.5 shows the average thrust coefficient over a single cycle. We can clearly see the mean Ct of C3 is higher than any other configuration. Representing this in terms of percentage compared to C1, C2 and C3 produce 14% and 25.1% higher mean thrust coefficient. The 10.6% difference between C2 and C3 confirms that, although a thicker foil produces more wake effects, for the investigated conditions, the overall thrust production is higher, hence more efficient, with a thicker forward foil. To further investigate and understand the physical reasons behind this phenomenon, we provide insight into velocity and vorticity fields.

Fig.6, 8,10 and Fig. 7, 9,11 show the contour plots at 3.7 cycles of the velocity in the x-direction and vorticity, respectively, for the various tested hydrofoil configurations. Regarding velocity fields, the contour plot for C1 (Fig. 6), for instance, indicates the wake is being generated towards the top of the forward hydrofoil. This area, characterised by high velocity gradients, is then propagated downstream and interacts with the aft foil. When comparing the three different configurations, we observe the size and magnitude of these high velocity gradient areas are lower in C1 (Fig.6), followed by C2 (Fig.8) and C3 (Fig.10). This leads us to believe the higher the thickness to chord ratio, the more impacting the wake generated. Studying the impact this wake has on the aft foil we see that the wake generated by the aft foil also increases if the incoming flow is more unsteady and turbulent. This points us to the fact that the thicker the forward foil, the more aft foil-wake interaction, which directly affects thrust production. We also notice the wake generated by the forward foil in C2 is somewhat similar to the wake generated by C3. However, the wake generated by the aft foil of C3 is observed to produce more velocity gradients in the wake than that of the aft foil of C2. This goes to show the effect of the forward wake is multiplied by the aft foil which is an important factor to consider for configurations with a very high forward foil thickness to chord ratio.

Regarding the contour plots for vorticity magnitude, for all three configurations, we notice the generation of four main vortices in distinct locations: the leading edge, trailing edge, and downstream areas of each foil. The centre of these vortices is consistent with the velocity plots above, where high gradients in velocity correspond to higher vorticity. By observing the magnitude of these vortices, we observe that the leading and trailing edge vortices hold the same conclusions as for the velocity plots, where the vorticity magnitude in C1 is more moderate, while C2 and C3 show similar behaviour. However, looking at the detached outer vortices we see a significant difference in all three configurations. The propulsion system with the larger thickness-chord ratio has a smaller outer vorticity in terms of magnitude. We believe this is due to the flow having higher vorticity which in turn aids and enhances the process of mixing of the flow leading to lower vorticity and faster wake recovery downstream. Another noteworthy effect to be considered is the detached outer vorticity that is being produced behind the aft foil is significantly greater than the forward foil. This behaviour can be best noticed for C1 in Fig.11 as the thickness-to-chord ratio of the aft and forward foil is the same, and it is caused by the increased turbulence and vorticity that the aft foil encounters. Overall, findings indicate the most efficient foil configuration is achieved with a thicker forward foil section. The forward foil produces more thrust as its thickness increases, and, although a stronger interaction between the forward foil-generated wake and the aft foil is observed, a higher overall thrust coefficient is achieved.

Table 2 List of Particulars



Particulars	
Vessel waterline length	2.27 m
Vessel longitudinal centre of gravity	0.156 m (from amidships)
Interfoil spacing (s%)	50%
Foil type	NACA-0008, NACA-0012, NACA-0015
Foil chord (c)	0.23 m
Aft foil phase shift (ϕ)	π
Pivot point	Leading edge
pitching amplitude (α_0)	±14.0deg
wave frequency (Ω)	$4\ rads^{-1}$
wave-induced velocity (u_0)	0.46 m/s
Fluid type	Seawater
Fluid temperature (T)	15˚C
Fluid density (ρ)	1026.021 kg/m3
Fluid dynamic viscosity (μ)	0.00122 Pa.s

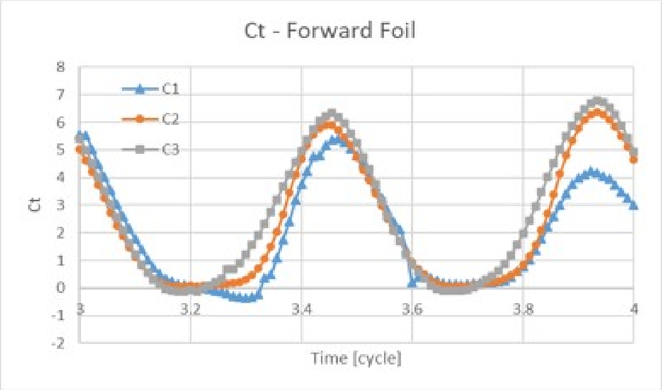


Fig. 3 Average Ct Plot Forward Foil

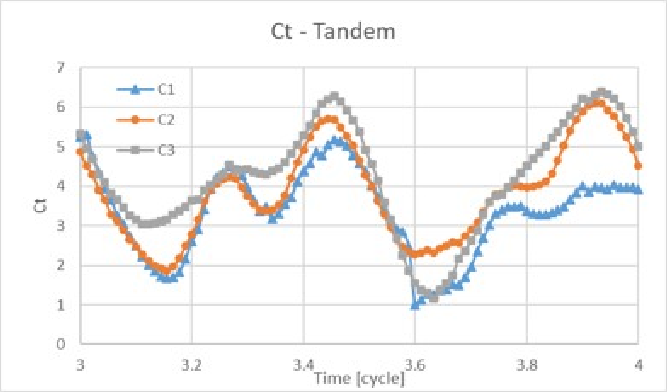


Fig. 4 Average Ct Plot Tandem Foils

Conclusion

The aim of this study was to determine the most efficient system out of the three configurations being tested and draw conclusions in order to make predictions and observe patterns that emerge. We were also trying to fill gaps that were there in other studies regarding some factors that were neglected, most common of which was wave orbital motion. This is something we included in our simulation as it provides us with the closest and most accurate set of conditions that can be achieved through computational methods. Keeping into consideration almost all the environmental effects apart from 3D foils we conducted simulations testing 3 different forward foil geometries, given in Table.1 and their corresponding configurations with a fixed aft foil geometry. We used three main simulations in order to quantify our results. Those were: Total thrust plot, Velocity magnitude plot in x-direction, Vorticity magnitude plot in x-direction. Plotting the thrust plots into graphs we could see a few parents start to emerge from which we could better understand the issue that plagued the system to help better the efficiency of the system.

Looking at the Ct plots in Fig.5 we can see the larger the thickens to chord ratio of the forward foil the greater is the total amount of thrust produced by the system. We can also observe that total Ct for C3 and C2 is overall somewhat similar while it is less for C1. This can be further supported when we look at the velocity plots for C1 in Fig.6 where there is less

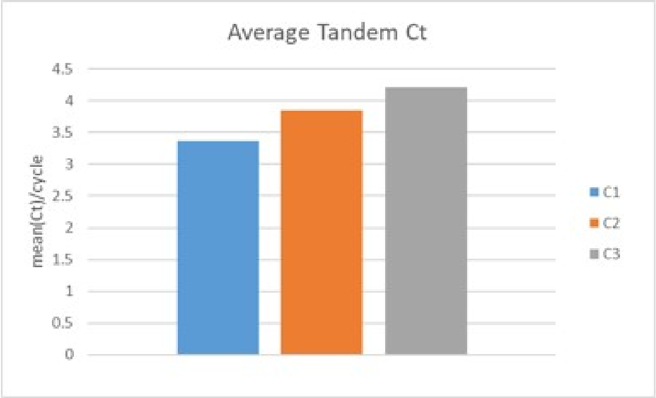


Fig. 5 Histogram Plot for Average Ct Tandem system

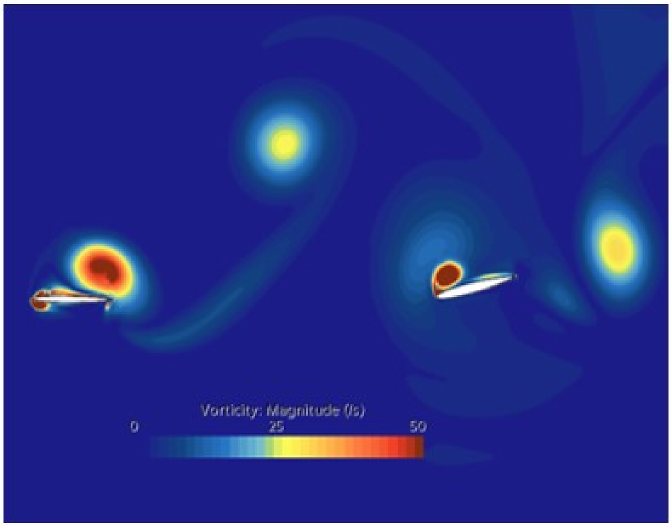


Fig. 6 Contour-Velocity Plot 3.7 Time-Cycle Configuration 1

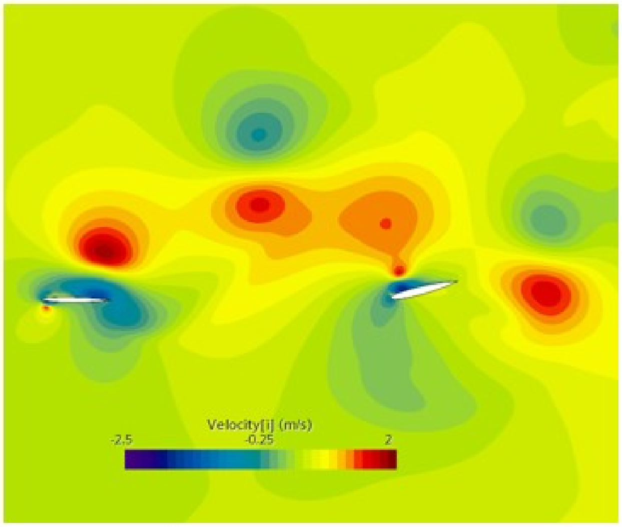


Fig. 7 Contour-Vorticity Magnitude 3.7 Time Cycle Configuration 1

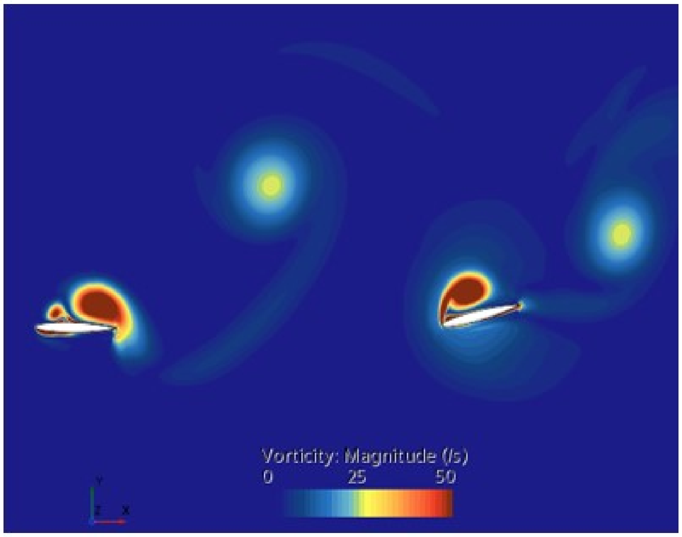


Fig. 8 Contour-Velocity Plot 3.7 Time Cycle Configuration 2

wake being generated compared to the other two configurations. In general, we notice the larger the section forward foil, the larger and the more impacting the wake on the aft foil at a given interfoil spacing. The opposite however is the case for the vortices that are being generated. Over there as we see in Fig.7,9,11 the larger the thickness to chord ratio the lower is the magnitude of the detached outer vorticy that we see being generated by both foils. Keeping in mind that the vortices that are produced close to the leading and trailing edge are actually increasing in magnitude with increase in thickness to chord ratio. We also observe in Fig.4 the total thrust being produced by the system is always the greatest for NACA0015 configuration except when the time cycle is at 3.7 there, we see the NACA0012 configuration exceed the NACA0015 configuration in terms of total thrust being generated. This can be attributed to the wake interaction during time cycle 3.7 which we can see in fig.8 and fig.10 how the C2 configuration has less wake interaction allowing for more total thrust. This goes to show lessening of the wake interaction between the two foils is the best way to improve the overall thrust of the system.

From our studies we conclude that the larger the thickness to chord ratio the larger the total thrust produced is. However, there is a trade-off in terms of wake interaction as a forward foil with the larger thickness to chord ratio in turn reduces the efficiency of the aft foil. The overall thrust produced should keep increasing with the thickness to chord ratio until the point where the forward foil wake is producing too much turbulent flow for

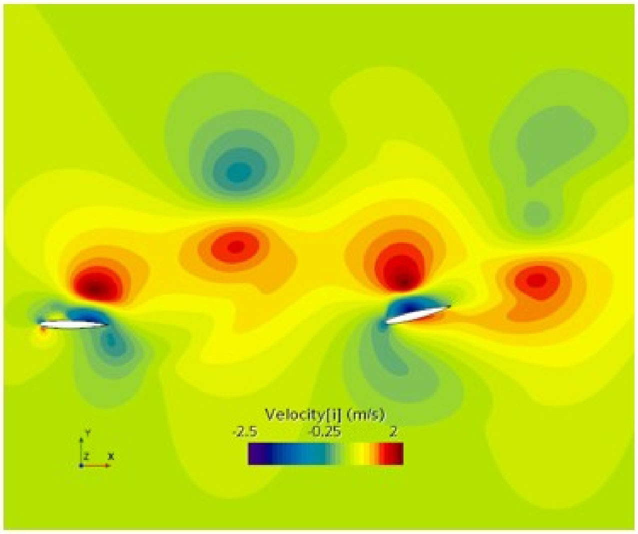


Fig. 9 Contour-Vorticity Magnitude 3.7 Time Cycle Configuration 2

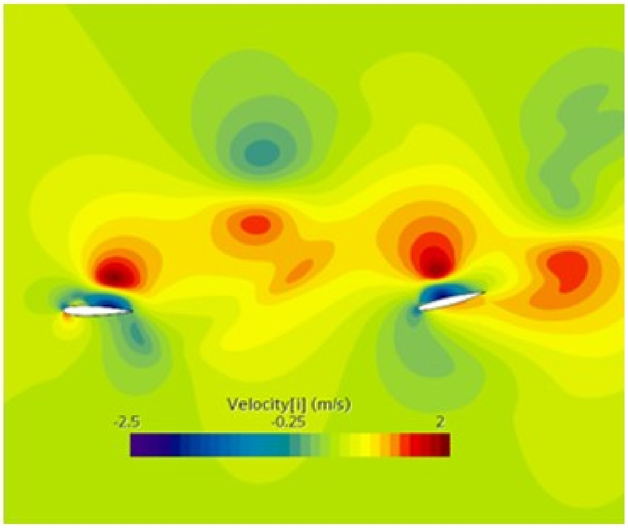


Fig. 10 Contour-Velocity Plot 3.7 Time Cycle Configuration 3

the aft foil to function. At which point we should see a sudden drop in total thrust produced over a full cycle. This drop does not occur till the highest configuration we tested however we do see a glimpse of it at 3.7 time-cycle in Fig.4. From all this we can say in conclusion our hypothesis that a thicker forward foil is more efficient, turned out to be true. We can further conclude that the for a system making use of this propulsion technique it is recommended that whatever the thickness of the aft foil be,(say NACA-0012) it is recommended to go up in thickness to chord ratio by a minimum factor of 3 (eg. NACA-0015) to see the most optimal thrust output for the given system of foils.

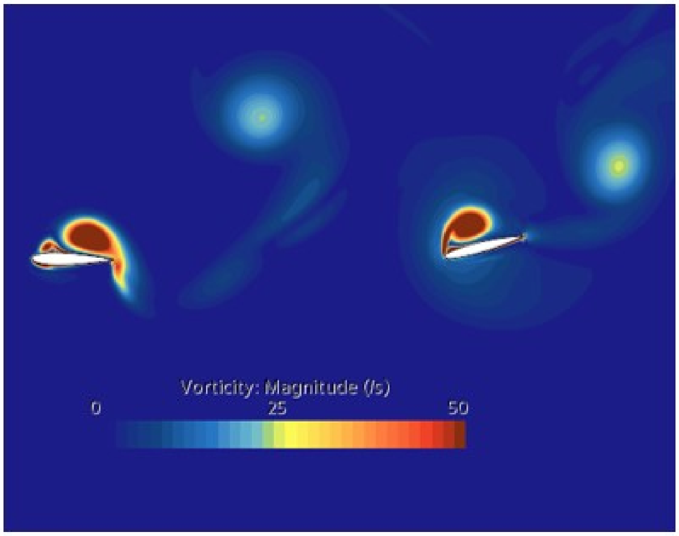


Fig. 11 Contour-Vorticity Magnitude 3.7 Time Cycle Configuration 3

All the simulations as mentioned previously were done with fixed parameters which have been carefully picked and derived through experimental data to most closely represent real conditions. Because of this we are quite confident that all results and conclusions drawn from our study are as accurate as is computationally possible. However, our study due to limitations with our software investigated these foils in a 2D world, which unfortunately does overlook some extra vortices that are generated only by 3D hydrofoils. Although it is important to note that when the data from past research papers with the same limitation was compared to experimental data it did not seem to be raising any significant errors. This gives us confidence in our results and accuracy, however, we would still recommend for any future studies to look into the effect of those vortices on the final thrust output. Alongside this other future work that can be done on this system is: Studying the thickness-to-chord ratio at which the system's total thrust starts to drop off (as talked about previously). Investigation into varying foil shapes of the aft foil. Studying wake interaction in a system of flexible hydrofoils. Impact of a variable and active interfoil spacing on total thrust produced and wake interaction.

References

1 K. Jones, *AIAA Journal*, **36**, 1240–.

2 R. Katzmayr, *NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS*, p. 1–6.

3 I. Akhtar, *Theoretical and Computational Fluid Dynamics*, 2–15.

4 L. Muscutt, *Journal of Fluid Mechanics*, **827**, 485–493.

5 M. Penglei, *Science Direct*, **214**, 431–441.

6 B. Ribeiro, *Physics Review*, 2–21.

7 A. Chipolina, *University of Southampton, Maritime Engineering Science*, 11–50.

8 Siemens, *Simcenter STAR-CCM+ V2021.2.1*, Siemens Industries Digital Software.

9 J. Anderson, *Image from introduction to aerodynamics*, `https://www.researchgate.net/figure/Fig1-Airfoil-nomenclature-source-Image-from-introduction-to-aerodynamics-by-John-D_fig1_292134281`, Retrieved from.