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Numerical Analysis of Reduced Frequency on Flapping Tandem Foils

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Abstract –*Numerous investigations on flapping wing motion have been conducted over the last two decades. The study of flapping wing motion was inspired by the possibility of using it to design and develop micro air vehicles. The application of flapping wing motion in power generation systems has attracted attention recently because of the growing need to replace fossil fuels with renewable energy sources. This research examines the effect of pitch oscillation frequency on the propulsion of a tandem flapping foils power generation system. Herein, the 2D models of tandem foils pitching with reduced frequencies (f*) of 0.04, 0.14, and 0.18 are used for parametric investigation. The results reveal that f* = 0.18 offers the optimal lift force among other reduced frequencies and 2.91% lower drag force compared to f* = 0.14.*

Keywords: *CFD, Flapping foil, Pitching, Reduced frequency, Tandem foil.*

Nomenclature

c	Chord length
C_d	Coefficient of drag
C_l	Coefficient of lift
C_T	Coefficient of thrust
CFD	Computational fluid dynamics
t/T	Dimensionless time
ρ	Fluid density
μ	Fluid dynamic viscosity
v	Fluid kinematic viscosity
FA	Front airfoil
MW	Mega Watt
MAV	Micro air vehicle
$\dot{\theta}$	Pitching rate
ω	Pitching rotation rate
θ	Pitching amplitude
f	Pitching frequency
h_a	Plunge amplitude
RA	Rear airfoil
k	Reduced frequency number
f^*	Reduced frequency number
U_{ref}	Reference velocity
Re	Reynolds number
t	Time
$\overline{C_l}$	The average coefficient of lift
$\overline{C_d}$	The average coefficient of drag

I. Introduction

Indonesia is demonstrating its seriousness to commit on "Net zero emission" to achieving renewable energy transitions by 2060 by actively campaigning for sustainable and environmentally friendly development [1]. According to 2014 statistics, theoretically, Indonesia has a hydrokinetic energy potential of 287,822 MW from ocean currents [2]. The most prominent strait is the Alas Strait in West Nusa Tenggara, with the highest water flow velocity exceeding 1.5 m/s. With the fact that water is ten times heavier than air, hydrokinetic power is considered to lead us to potential green energy extraction from the water currents.

There are four different kinds of turbines according to their conversion of hydrokinetic power to electricity. These devices are horizontal axis turbine, vertical axis turbine, hybrid turbine, and oscillating or flapping foil turbine. The horizontal axis turbine is the most common with its axis of rotation parallel to the fluid flow. The vertical axis turbine has an axis of rotation that is perpendicular to the fluid flow. There are several types of vertical axis turbines such as Darrieus and Savonius turbines. The rotor of a hybrid hydrokinetic turbine is the combination of both Darrieus and Savonius turbines' rotors. This rotor has the characteristics of both turbines and shows high efficiency and good starting capability [3].

The flapping foil turbine uses one or more foils to convert hydrokinetic power into a flapping motion that, in the end, rotates the generator. Its wide sweeping area convinced us to become more efficient in extracting hydrokinetic energy. These facts motivated us to develop a flapping foil power generator turbine. Earlier studies have demonstrated that a flapping foil turbine can reach up to 18 % higher efficiency (power output/ power input) than conventional turbines [4]. The high efficiency of this flapping turbine is expected to absorb the kinetic energy carried by the seawater flow and thus generate electricity for the required areas in Indonesia. Besides, the flapping foil turbine requires more research to find its efficiency to extract hydrokinetic power from the water current.

One of the parameters that affects the efficiency of the flapping foil turbine is flapping frequency. In this research, we use three variations of reduced frequency which is the non-dimensional form of frequency: 0.04,

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0.14, and 0.18.

In the Literature Review recent publications on flapping foil turbines are analyzed. In Research Objective, many articles on tandem flapping foils are discussed, each paper's important findings are highlighted, and the aim of this paper is stated. In the next section, Materials and Methods, the information regarding the computational model and the simulation setup are given in detail. In the Analysis, the simulation results are analyzed and explained using the help of flow visualization. Lastly, in Conclusion, the main result of this research is carefully compiled and the suggestion for future works is discussed.

II. Literature Review

The field of flapping wing flight has been progressing significantly in the last three decades as numerous researchers have attempted to understand how creatures, such as insects or birds, fly. Some recent studies on insects are done by Kunicka-Kowalska et al. [5] and Harvey et al. [6].

A study about the flapping butterfly wing mechanism had been done by Kunicka-Kowalska et al. [5] by using three cameras on three different axes to capture the wing mechanism. The real butterfly was scanned and converted into a numerical model. The numerical model was then simulated using CFD until the force data were obtained. This study concluded that the forward flight is induced by the wing shape and the flapping mechanism. This study could lead us to the design of a flapping wing mechanism that resulted in a forward flight.

A review done by Harvey et al. [6] summarized that the natural flight of birds and insects has impacted aeronautical science. A lot of inspiration for aircraft design came from biological natural flights. Flying animals use flapping wing kinematics to generate lift and thrust. However, the design of a flapping wing faces a big challenge in the scaling-up effects of the flapping wings. It is caused by the rigid man-made structure that cannot adapt to the environment like the flexible and thin wing structures found on flying animals.

Several breakthroughs have been achieved in understanding flapping wing flight, such as the critical phenomena in the low Reynolds number regime. Further, flight phenomena, such as leading-edge vortices and spanwise flow [7], wing-wake interactions [8], and rapid wing-rotation [9], [10] have been investigated. Research in flapping-wing flight has led to their application in designing and developing flapping wings for vehicles, such as the micro air vehicle (MAV) [11]. Researchers have focused on applying the flapping mechanism to wind and water turbines, which led to the development of the flapping foil turbine. Researchers have reported the following advantages of flapping foil turbines over rotary turbines [4].

- A flapping foil turbine requires a lower speed than that required by a rotary system turbine for the same power coefficient; therefore, it is safer from a safety perspective.
- The shape of the flapping foil turbine blade is simple, and its production is easy compared with the twisted shape of the rotary turbine blade [4].
- A flapping turbine can achieve a higher efficiency (maximum of approximately 18%) compared with a conventional rotary turbine (one that rotates about an axis) [4].

Research and development milestones of the flapping foil turbine over the years:

- The University of Strathclyde built and tested an oscillating hydrofoil turbine (Stingray) in 2005–2006. The major challenge in operating Stingray has been the complexity of the turbine system with many variables (including mechanical losses due to the actuator mechanism) [12].
- Canada carried out a project to design and test an oscillating hydrofoil turbine in a lake in 2010 [13]. The test results indicated that the power extraction efficiency was 40% (equivalent to a modern rotor-based generator); however, mechanical losses due to the clutch mechanism were approximately 25%.

III. Research Objectives

Numerous investigations on tandem flapping airfoils/wings have been conducted. A recent numerical analysis was performed on rectangular tandem airfoils (2D) and wings (3D) at a Reynolds number of 1000 with two different aspect ratios of 2 and 4 [14]. Arranz's [14] study on the difference between flapping airfoils and wings revealed that the change from 2D to 3D affects thrust generation more than lift. The effects of the vertical spacing or gap between two NACA0012 airfoils at high angles of attack of 30° to 90° were numerically investigated in [15]. An interesting finding was that the pattern of the lift-to-drag ratio in all tandem cases was highly similar to that of a single airfoil. Essentially, being configured in tandem does not improve the total lift-to-drag ratio.

A numerical study on a double undulatory NACA0012 airfoil with a Reynolds number of 195000 examined the undulatory airfoil's performance in harvesting energy from fluid [16]. The horizontal spacing and the flapping-motion phase difference between the fore and aft airfoils were examined. This study concluded that two isolated single airfoils harvested more energy than tandem airfoils.

Another numerical study on a tandem NACA0012 airfoil was conducted by Bie [17]. The tandem airfoil was flapped at a Reynolds number of 34410, and the vertical spacing between the airfoil and pitch angle (both of which were defined in polar coordinates) was examined. This study concluded that different spacing and pitch angle combinations could increase the lift by 78.1 % or decrease it by 51.6 %.

Chen [18] conducted a numerical study on two elliptical airfoils plunging or flapping vertically under various angles of attack, plunging and pitching phase angles, and horizontal spacing between tandem airfoils at a Reynolds

number of 5000. The results of the tandem airfoil were compared with those of the isolated fore and aft airfoils. The findings of this study were: (1) the thrust was proportional to the angle of attack; (2) a setting where a hind/aft airfoil led an aft airfoil was beneficial for lift and thrust generation; and (3) the ratio of horizontal spacing: chord length of 1.5:2 enhanced lift and thrust, whereas at a ratio of 3, a reduction in both the lift and thrust were observed.

More complex parameters have been studied more recently. For example, a group of researchers [19] studied the effects of jet flow as an active flow control technology on the NACA6415 airfoil. The study was conducted numerically at a Reynolds number of 70000. The primary conclusion was that airfoils with jet flow typically have better lift and thrust characteristics than those without jet flow. Another group studied the thermal effects of ground effects on two tandem NACA 0012 airfoils at a Reynolds number of 500 [20]. This study discovered that two tandem airfoils are more aerodynamically efficient than the two in isolation, mainly when the fore airfoil is above the aft.

These investigations reveal that numerous parameters affect the aerodynamic performance of a tandem airfoil/wing, such as the geometry of the airfoil/wing, vertical and horizontal spacing, angle-of-attack or pitch angle, flapping kinematics (for example, plunging, pitching, and combined pitching and plunging), and phase differences in plunging and pitching motions. Moreover, combining two or more of these parameters yields varying results, where improvement or deterioration in lift and thrust generation might be observed. In conclusion, the correlations between these parameters cannot be generalized to all flapping wing configurations.

In this study, the relationship between the factors of the flapping wing and the optimal combination of these factors were numerically investigated for use in designing hydro/marine power plants inspired by the motion of insect wings.

The primary goal of our research was to analyze the effect of reduced frequency on the forces and moments of a tandem flapping foil with a Reynolds number (Re) of 100000.

IV. Materials and Methods

The investigations of the effects of reduced frequency on oscillating tandem foils are performed based on computational fluid dynamics using ANSYS FLUENT version 17.1. Simulations are limited to 512000 total grid elements using the student version of FLUENT.

The model is constructed using the Design Modeler program in ANSYS FLUENT. The geometric parameters of the model are a chord length of 0.1 m, a stagger distance between two foils of 0.2 m. and the aerodynamic center located at $0.25c$ of the foil's leading edge. The stagger distance between two foils is measured from the aerodynamic center of the front airfoil to the aerodynamic center of the rear.

The 2D model of the tandem NACA0012 foil is shown in Fig. 1, and the oscillating pitching motion of the foil is shown in Fig. 2. The oscillating pitching motion is expressed with periodic symmetrical function as shown in Equation 1.

$$\dot{\theta}(t) = \omega\theta \cos \omega t \quad (1)$$

$$\omega = 2\pi f \quad (2)$$

Where $\dot{\theta}$ is the pitching rate, θ is the pitching amplitude, ω is the pitching rotation rate (Equation 2), f is the pitching frequency.

A rectangular grid domain is used on the model with a total of 367572 grid elements, as shown in Fig. 3. The zoomed-in boundary layer at the foil's leading and trailing edges are shown in Fig. 4.

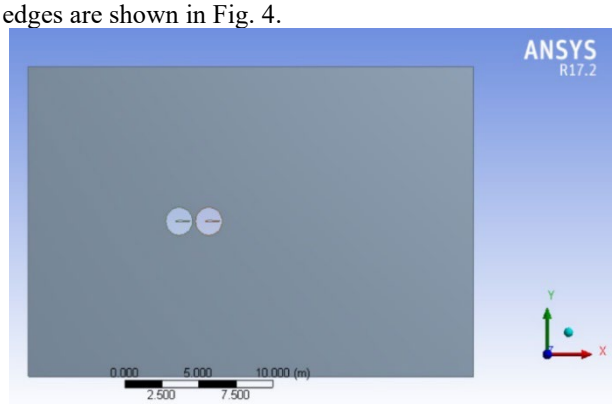


Fig. 1. The 2D Model of Tandem NACA0012 Foils.

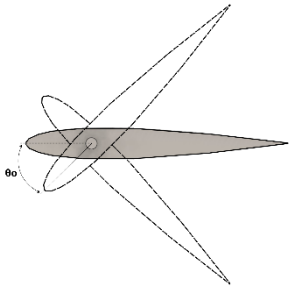


Fig. 2. Oscillating Pitching Motion of Airfoil.

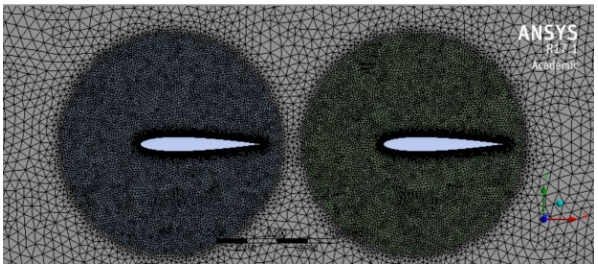


Fig. 3. Meshing of 2D Tandem NACA0012 Foils.

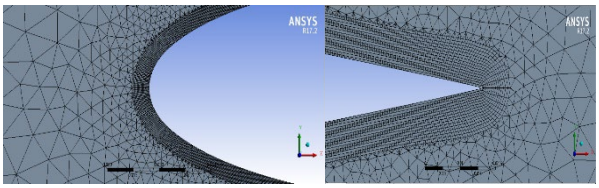


Fig. 4. Zoom-in Boundary Layer. Left: Leading Edge Foil; Right: Trailing Edge Foil.

The meshed model is imported into the ANSYS FLUENT to set-up the simulations. A viscous *k–ω* SST model is used in the simulation. The fluid flow used has a density (ρ) of 1030 kg/m^3 and dynamic viscosity (μ) of 1,07 × 10^{-3} kg/ms, thus rendering it almost identical to sea water at 20°C.

The tandem foils are pitching harmonically in a forward flight with a velocity of 2,572 m/s (U_{ref}). The Reynolds number of the simulations is 247585 (Equation 3).

$$Re = \frac{\rho U_{ref} c}{\mu} \quad (3)$$

The variables used in this investigation are the reduced frequency f^* of 0.04, 0.14, and 0.18, calculated using Equation 4.

$$f^* = \frac{fc}{U_{ref}} \quad (4)$$

Where c is the chord length, f is the pitching frequency, U_{ref} is the reference velocity of 2,572 m/s.

IV.1. Validations

Validation compares CFD results with available data to prove a model's ability to reproduce physics (NASA, 1988). This study performs validation by comparing the duplicated model tested by Tuncer and Platzer [4]. A single NACA0012 foil with a plunging motion flowing in the air is used as the test model. The plunging motion is simulated using turbulent flow (Reynolds Number, $Re = 3 \times 10^6$) and a plunge amplitude, h_a = 0.4. The Reynolds Number for the validation cases is calculated using Equation 5. The numerical results of Tuncer and Platzer are compared with the simulation using the turbulent *k–ω* SST model.

$$Re = \frac{2\pi f h_a c}{v} \quad (5)$$

Where v is the fluid kinematic viscosity.

The reference data used to validate the study are the time-averaged thrust coefficient (C_{Tmean}) compared to the reduced frequency f^*. The variations of f^* are 0.3, 0.5, and 1. The data of Tuncer and Platzer (Fig. 5) is imported into the Engauge Digitizer program to obtain the exact coordinates. The validation results are listed in Table I. Evidently, the current simulation results match the reference data. Therefore, the validation process is valid.

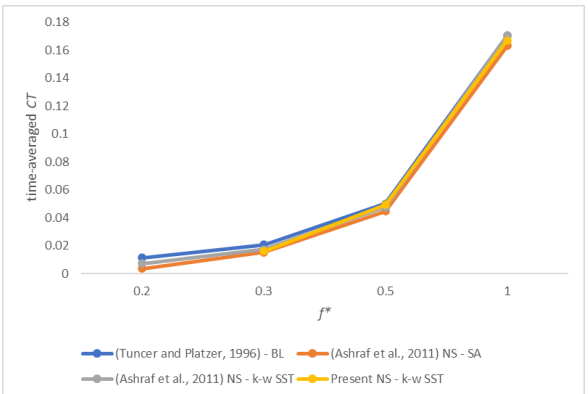


Fig. 5. C_{Tmean} vs. k Plunging Single NACA0012 Foil.

TABLE I.
VALIDATION PROCESS OF PLUNGING SINGLE NACA0012 FOIL
h_a = 0.4, $Re = 3 \times 10^6$

f^*	(Tuncer & Platzer) $C_{T\,mean}$	Simulation $C_{T\,mean}$	Error (%)
0.3	0.0163	0.0160	1.78
0.5	0.0477	0.0494	3.52
1	0.1703	0.1670	1.94

V. Results

This numerical study investigates the influence of reduced frequency on the drag, and lift, of 2D tandem foils. With the current Reynolds number (*Re*) regime (247,585), the flow is assumed to transition from laminar to turbulent; therefore, the k–ω SST turbulence model is selected. The reduced frequency (f^*) determines the pitch motion (fast or slow) of the simulated tandem foils because it affects the pitch oscillation frequency. Therefore, the parameter values used herein are f^* = 0.04, 0.14, and 0.18, with a pitch motion frequency of f = 1.0288, 3.6008, and 4.6296 Hz, respectively. Moreover, the other factors, such as the amplitude of the pitch of the tandem foil, are set to a maximum angle $\theta = 35°$, where the two foils move together.

V.1. Average Drag and Lift Coefficient

TABLE II.
AVERAGE DRAG AND LIFT COEFFICIENT OF FRONT AND REAR FOILS WITH VARIATION OF REDUCED FREQUENCY.

f^*	$\overline{C_d}_{FA}$	$\overline{C_d}_{RA}$	$\overline{C_l}_{FA}$	$\overline{C_l}_{RA}$
0.04	0.5658	0.3030	0.0143	0.0058
0.14	0.5999	0.4378	0.0595	0.0597
0.18	0.4718	0.5356	0.0953	0.0549

In Table II, the time average output parameter is computed by averaging the values obtained from the FLUENT calculation: drag and lift of the front and rear foils with three different reduced frequencies as the tested parameters. Note that $\overline{C_d}$ stands for the average drag coefficient and $\overline{C_l}$ for the average lift coefficient. The subscript FA stands for the front foil, and the subscript RA for the rear foil.

TABLE III.
$\overline{C_d}$ OF PITCHING TANDEM FOILS SIMULATION WITH PARAMETER f^*.

f^*	$\overline{C_d}_{FA}$	$\overline{C_d}_{RA}$	$\overline{C_d}_{total}$
0.04	0.5658	0.3030	0.8688
0.14	0.5999	0.4378	1.0377
0.18	0.4718	0.5356	1.0075

TABLE IV.
TIME (T) OF THE TANDEM FOILS PITCHING SIMULATION PRODUCES THE

MAXIMUM AND MINIMUM DRAG FOR PARAMETER f^*.

	C_d			
f^*	$C_{d\,FA}$		$C_{d\,RA}$	
	$C_{d\,FA\,max}$	$C_{d\,FA\,min}$	$C_{d\,RA\,max}$	$C_{d\,RA\,min}$
0.04	0.69T	0.96T	0.85T	0.94T
0.14	0.73T	0.5T	0.67T	0.5T
0.18	0.74T	0.45T	0.69T	0.43T

Considering the positive values of the drag produced, thrust is not generated because the positive value of the drag coefficient, C_d is defined in the same direction as the fluid moving through the foil. Table III lists the time-averaged total drag coefficient of the pitching tandem foils with reduced frequency variations. Table IV lists the time when the tandem foils produce the highest drag for the parameter f^*. The value of the time-averaged drag coefficient shows that the highest reduced frequency does not generate the highest average drag coefficient. However, f^* = 0.14 generated the highest total drag coefficient among the other reduced frequency parameters. The total drag value when f^* = 0.18 is marginally lower than that when f^* = 0.14 for 2.91 %. Furthermore, the total drag value for f^* = 0.04 is the lowest among the other reduced frequency parameters. These results indicate that an optimal frequency for the pitching tandem foils exist thus, large drag forces can be avoided by cautiously selecting the operational frequency. Meanwhile, the minimum drag occurs almost simultaneously for both front and rear foils.

TABLE V.
$\bar{C}_l$ OF PITCHING TANDEM FOILS SIMULATION WITH f^*

f^*	$\bar{C}_{l\,FA}$	$\bar{C}_{l\,RA}$	$\bar{C}_{l\,total}$
0.04	0.0143	0.0058	0.0201
0.14	0.0595	0.0597	0.1192
0.18	0.0953	0.0549	0.1502

TABLE VI.
TIME (T) OF THE TANDEM FOILS PITCHING SIMULATION PRODUCES THE MAXIMUM AND MINIMUM LIFT FOR PARAMETER f^*.

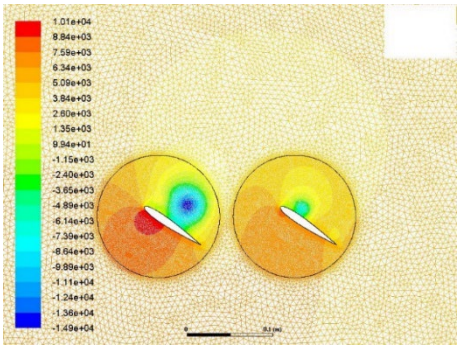
	C_l			
f^*	$C_{l\,FA}$		$C_{l\,RA}$	
	$C_{l\,FA\,max}$	$C_{l\,FA\,min}$	$C_{l\,RA\,max}$	$C_{l\,RA\,min}$
0.04	0.68T	0.18T	0.85T	0.36T
0.14	0.7T	0.21T	0.62T	0.12T
0.18	0.64T	0.13T	0.65T	0.16T

As presented in Table V, a significant difference is observed in the value of the lift coefficient, C_l for each foil for various frequencies tested. In this case, the obtained values of C_l are all positive, indicating the generation of a lift force instead of a downforce. Table VI lists the time the tandem foils produced the optimum lift. In Table V, the highest total lift coefficient is obtained from the simulation at the highest reduced frequency, f^* = 0.18, whereas the lowest total lift coefficient production is obtained from the simulation when f^* = 0.04. The total lift coefficient at $f^* = 0.14$, is in between f^* = 0.18 and f^* = 0.04.

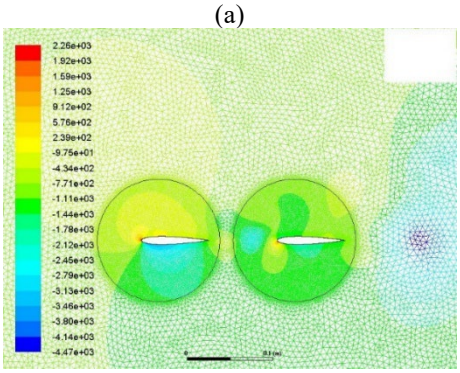
In Table VI, at f^* = 0.18, we can see that the lift coefficient of the front foil reaches the maximum lift, higher than that of the other reduced frequencies and at the same time as the rear foil. Therefore, the total lift coefficient is higher than the other frequencies. These results indicate that the 2D pitching tandem foils NACA0012 is suited for obtaining a large lift force using high frequency because the lift force increases when a higher frequency is applied.

VI. Discussion of results

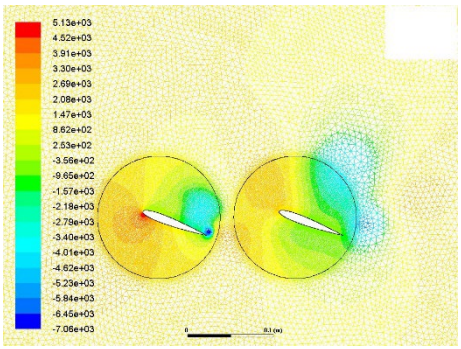
Figs. 6 (a), (b), (c), (d), (e), (f), (g), and (h) below show the pressure contours of each case as the drag coefficient varies with changes in the reduced frequency. Evidently, the red legend of the figure shows the highest-pressure area, whereas the blue legend represents the lowest pressure.



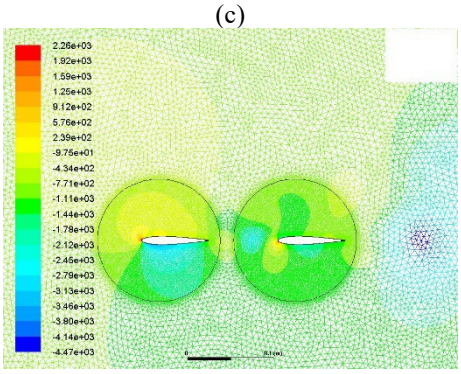
(a)



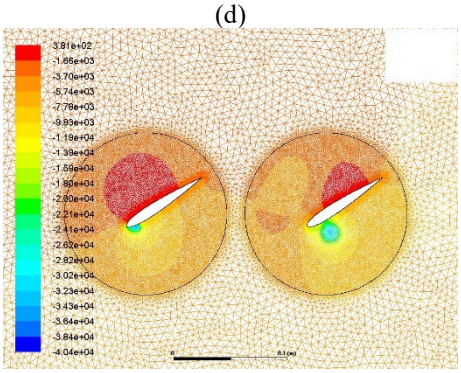
(b)



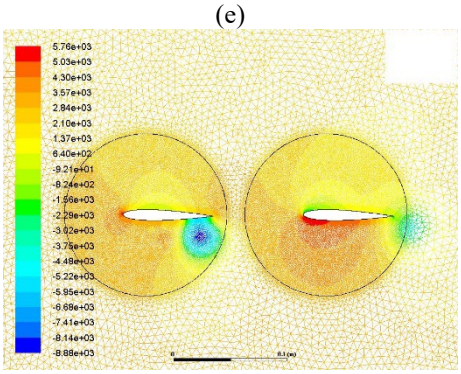
(c)



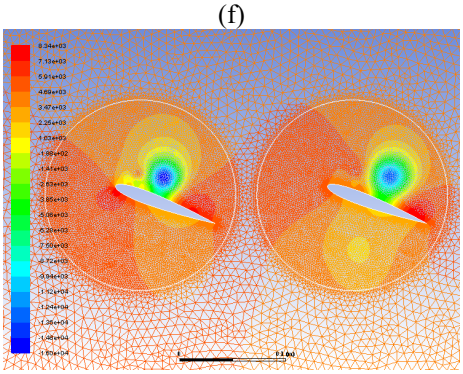
(d)



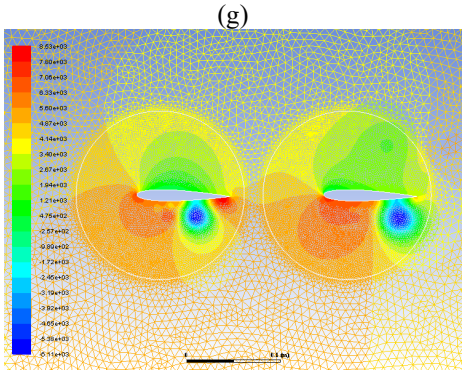
(e)



(f)



(g)



(h)

Fig. 6. (a) $C_{d\,FA}$ maximum when $f^* = 0.04$; (b) $C_{d\,FA}$ minimum when $f^* = 0.04$; (c) $C_{d\,RA}$maximum when $f^* = 0.04$; (d) $C_{d\,RA}$minimum when $f^* = 0.04$; (e) $C_{d\,FA}$ and $C_{d\,RA}$ maximum when $f^* = 0.14$; (f) $C_{d\,FA}$ and $C_{d\,RA}$ minimum when $f^* = 0.14$; (g) $C_{d\,FA}$ and $C_{d\,RA}$maximum when $f^* = 0.18$; (h) $C_{d\,FA}$ and $C_{d\,RA}$minimum when $f^* = 0.18$.

Fig. 6 can be used to investigate the simulation with the f^* parameter of the oscillating tandem foils at a pitch angle close to the maximum that produces the largest drag force. The lowest drag force was generated when the tandem foil oscillation reached a neutral position as shown in Figs. 6 (b), (d), (f), and (h). Fig. 6 (g) shows low-pressure contours on the upper surface of the tandem foils when reaching the maximum drag forces. Meanwhile Fig. 6 (h) shows low-pressure contours on the lower surface of the tandem foils when reaching the minimum drag forces.

Fig. 6 (e) shows that at $f^* = 0.14$ a contrasting pressure contour where the red area around the foil surface is more visible, thus indicating that the area has the highest pressure. Subsequently, each simulation displayed the pressure contours of the tandem foils that created the vortex while it is in oscillating motion. At the highest frequency, $f^* = 0.18$, the vortices occur on the upper surfaces of both foils when the position of the tandem foils is pitching up (Fig. 6 (g)).

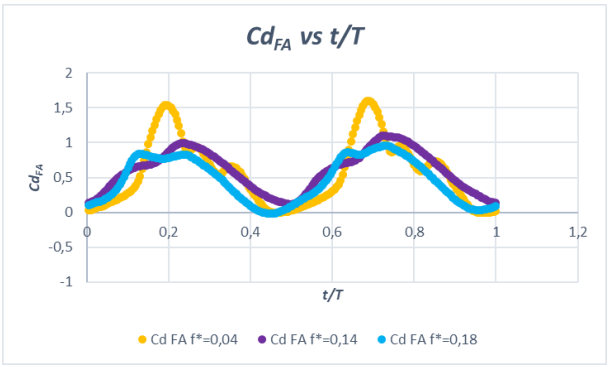


Fig. 7. $C_{d\,FA}$ vs t/T on parametric study f^*.

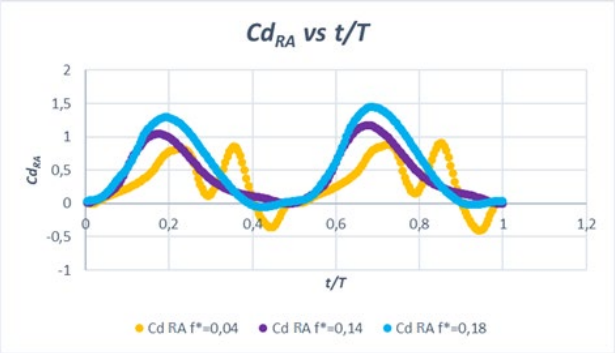
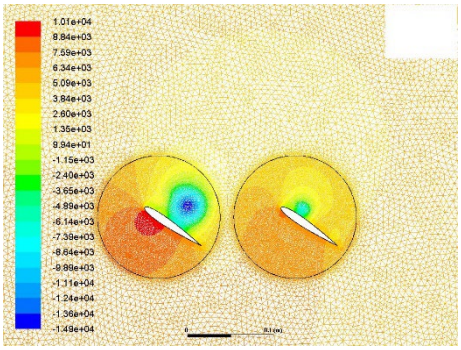
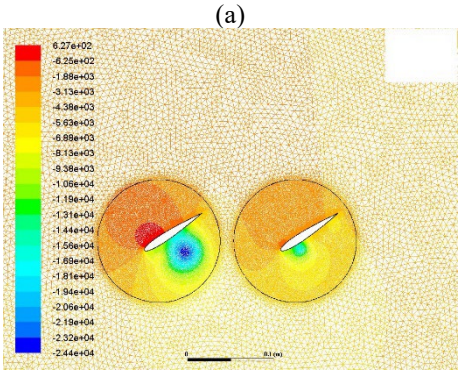


Fig. 8. $C_{d\,RA}$ vs t/T on parametric study f^*.

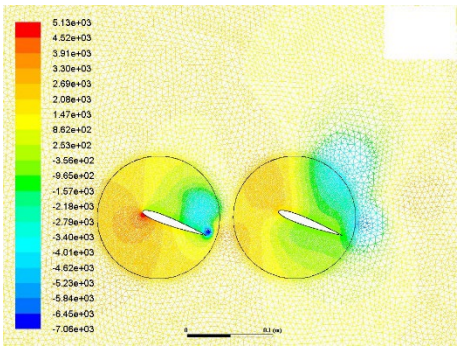
Figs. 7 and 8 show C_d vs. t/T plot of the 2D pitching tandem foils NACA0012 (i.e., the drag coefficients are plotted against dimensionless time). The time indicated by t/T ranges from instantaneous time $t = 0T$ to $t = 1T$. Both figures demonstrate that the simulation of tandem foils pitching with reduced frequency parameters exhibited approximately the same trend for each case as observed from the drag force generated by the front and rear foils using three different reduced frequency variations: f^*= 0.04, f^* = 0.14, and f^* = 0.18. When f^* = 0.04, thrust may be generated as shown by the orange curve in Fig. 7; some coordinate points on the C_d vs. t/T graph were negative or below the x-axis. Essentially, the pitch-oscillating tandem foils system produced thrust when the C_d values are negative. However, overall, the simulation results exhibit the same trend toward producing drag instead of thrust.



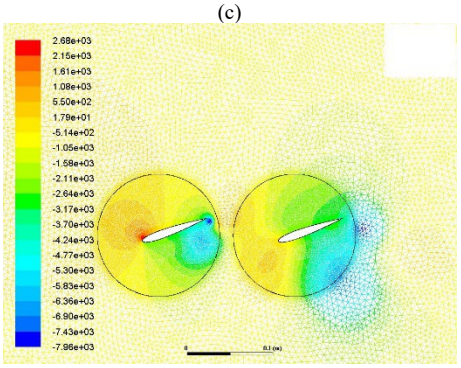
(a)



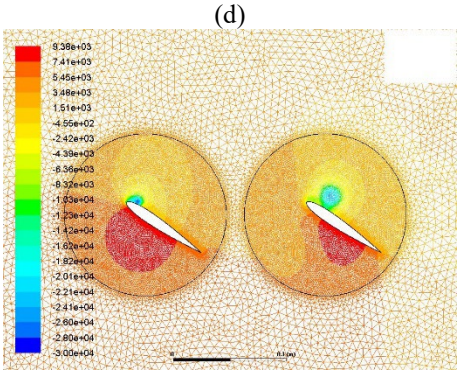
(b)



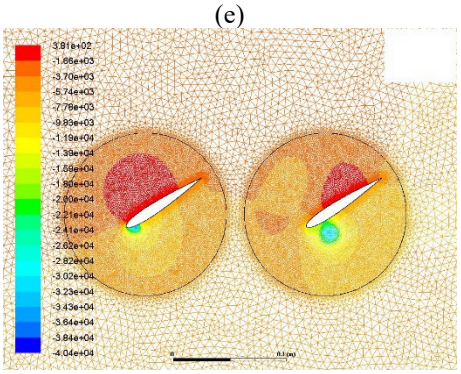
(c)



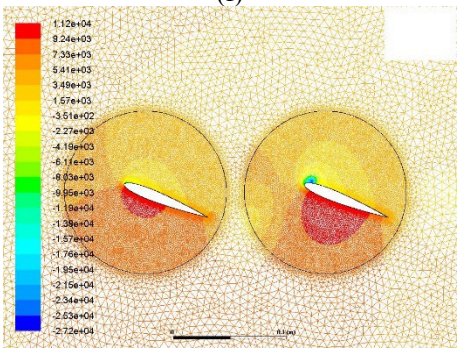
(d)



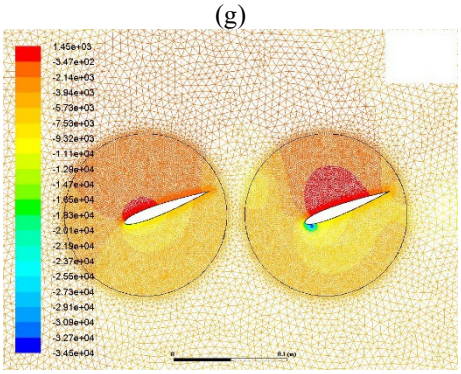
(e)



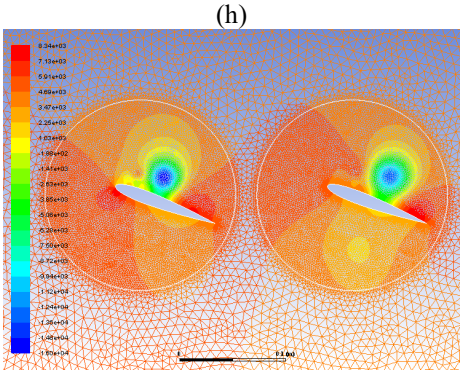
(f)



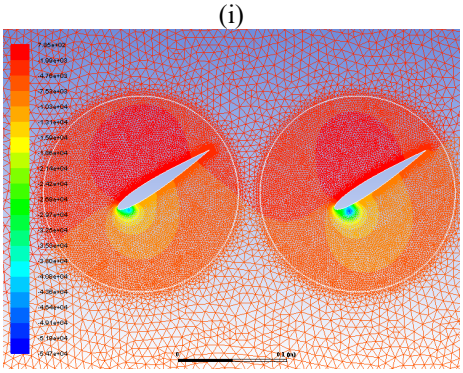
(g)



(h)



(i)



(j)

Fig. 9. (a) $C_{l\,FA}$ maximum when f^* = 0.04; (b) $C_{l\,FA}$ minimum when f^* = 0.04; (c) $C_{l\,RA}$ maximum when f^*= 0.04; (d) $C_{l\,RA}$ minimum when f^*= 0.04; (e) $C_{l\,FA}$ maximum when f^*= 0.14; (f) $C_{l\,FA}$ minimum when f^*= 0.14; (g) $C_{l\,RA}$maximum when f^*= 0.14; (h) $C_{l\,RA}$minimum when f^*= 0.14; (i) $C_{l\,FA}$ and $C_{l\,RA}$ maximum when f^* = 0.18; (j) $C_{l\,FA}$ and $C_{l\,RA}$ minimum when f^* = 0.18.

The maximum lift forces generated by the pitching tandem foils for the three frequency parameter variations exhibit similar characteristics. The maximum lift generated by the pitching tandem foils occurred immediately before the oscillation reached a maximum angle of 35°. When the tandem foils oscillate facing upward, that is, when the maximum instantaneous lift is generated, the position of the tandem foils block the fluid flow. They create a red pressure contour around the bottom surface of the tandem foils indicating that the pressure below the foil's surface is more significant than that at the top surface. Figs. 9 (e) and (g) show the high-pressure contours at the bottom surface of the foils when the tandem foils oscillate upward and reaches the maximum pitch angle.

The simulations with parameter f^* = 0.14 and 0.18 exhibit the formation of a vortex right around the leading edge, which triggers the leading-edge vortex (LEV) causing maximum lift force (Figs. 9 (g), and (i)). Thus, the lift is generated in the vortex area because of the resultant high-pressure and low-pressure regions. A high total lift force can also be obtained because both front and rear foils reached their maximum lift coefficient almost simultaneously. Meanwhile, the simulation with at f^* = 0.18 reached a higher total lift coefficient because the front foil generated a higher lift coefficient than the front foil at f^*= 0.14.

Meanwhile, as we can see in Figs. 9 (b), (d), (f), (h), and (j), the minimum lift occurs when the tandem foils face downward (nose down), creating high pressure on the top surface and generating a downforce instead of a lift.

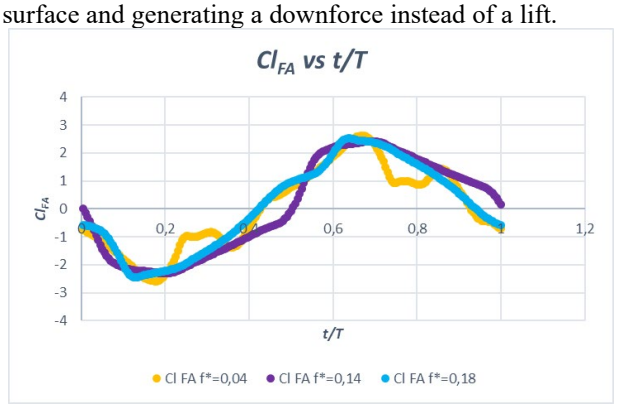


Fig. 10. $C_{l\,FA}$ vs t/T on parametric study f^*.

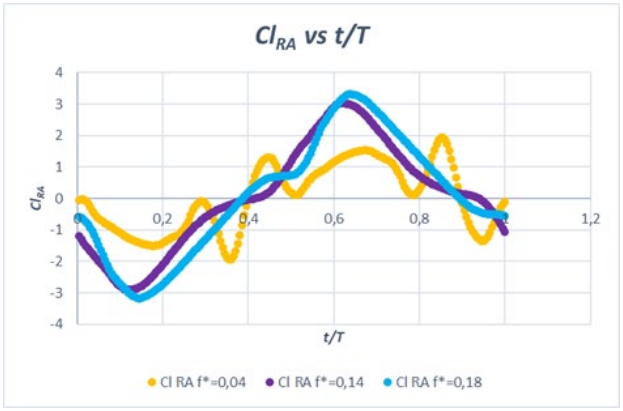


Fig. 11. $C_{l\,RA}$ vs t/T on parametric study f^*.

Figs. 10 and 11 show the C_l vs. t/T plot of the 2D pitching tandem NACA0012 foils (i.e., the lift coefficients are plotted against dimensionless time). The time indicated by t/T ranges from instantaneous time $t = 0T$ to $t = 1T$. Both figures represent the lift force generated by the front and rear foils using three different reduced-frequency variations, f^* = 0.04, f^* = 0.14, and f^* = 0.18.

They demonstrate that the maximum instantaneous lift produced by the simulation of tandem foil pitching with reduced-frequency parameters is not significantly different. However, the lift coefficient $C_{l\,total}$ for the parameter f^* = 0.04 is the lowest in the simulations when evaluated from the average value. The highest $C_{l\,total}$ was produced by f^* = 0.18. The C_l vs. t/T curve graphs for all

simulation cases exhibit coordinate points partly above and below the x-axis. The tandem foils pitching simulation indicates that lift and downforce can be produced. On average, this configuration produces a lift, as indicated by the positive $C_{l\ total}$value.

VII. Conclusion

The research results indicate that a faster pitching motion increases lift. Regarding the drag coefficient, the parameter $f^* = 0.14$ produces the highest drag coefficient of 1.0377, followed by $f^* = 0.18$ (1.0075) and $f^* = 0.04$ (0.8688). Further, the lift coefficient for $f^* = 0.18$ is the highest at 0.1502, followed by $f^* = 0.14$ (0.1192) and $f^* = 0.04$ (0.0201). At $f^* = 0.14$ and $f^* = 0.18$ the tandem foils reach higher maximum lift because the vortex shed by the front foil interacts with the flow of the rear foil. Therefore, the parameter $f^* = 0.18$ generates the best result because the tandem foils pitching system produce an optimal lift force among the rest of the parameters and a relatively smaller drag force (2,91 %) than $f^* = 0.14$. The findings of this study regarding the optimum range of the reduced frequency of pitch motion can be used to design flapping/oscillating turbines and provide data on the best operational conditions for turbines.

There are several suggestions for further research. First, it will be interesting to know the effects of having more foils in the flapping foil turbine. This knowledge is needed because in the future a marine current farm with multiple flapping foil turbines might be built. Secondly, study on various parameters that might influence the energy conversion such as pitching amplitude and phase difference between the front and rear foils. Lastly, researchers can study a combination of plunging and pitching motion on tandem foils and compare the results with the current research that uses pure pitching motion.

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