Effects of root chord movement on thrust generation of oscillatory pectoral fins

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Abstract

Fin kinematics is the key to thrust generation of oscillatory pectoral fins of manta rays. This could be one of the main reasons that fin designs of robotic manta rays are becoming more complex to simulate the fin kinematics more closely so as to generate high thrusts. However, as the trend suggests, the extent of improvement to thrust generation might not be worth the complexities added to the designs. Out-of-the-box design changes that favour the simplicity and yet improve the fin performance can be a sound replicate for the complicated fin design features. One aspect of manta rays’ pectoral fins that influences the fin kinematics is the constraint imposed on the movement of their particularly long root chord that is entirely attached to the body of manta rays. Hypothetically, reducing such a constraint can promote the angle-of-attack during flapping, which can improve thrust generation. This paper aims to study if the simple idea of disengagement of the fin root chord from the body, which is obviously a deviation from the nature, can improve thrust generation. An experiment was conducted on thrust generation of four basic fin designs, where different portions of their chord was disengaged from the body step-by-step. It was found that the fins with free root chord (minimal attachment to the body) could generate thrust slightly less than the fully constrained fins (full attachment). In addition, it was shown that thrust generation efficiency kept increasing while disengaging the chord further, and reached the maximum for free root chord. This may show that a powerful and yet more efficient fin can be produced with such a deviation from the nature.

1. Introduction

The thrust generation capability of oscillatory pectoral fins of manta rays has motivated many researchers to design similar propulsive mechanisms for locomotion of underwater vehicles [1]. The pectoral fins of manta rays can generate high amount of thrust [2, 3] that enables manta rays to cruise at high speeds [4, 5], exhibit high manoeuvrability such as turn-on-a-dime [5, 6], glide for energy conservation [7], and maintain stability during locomotion in the turbulent sea [2]. The capability of these fins for thrust generation under the abovementioned various swimming conditions can be linked to the kinematics that their fin body can exhibit [8–10]. More specifically, the large dorsoventrally-flattened body of these fins is elongated and supported with soft rays that deform the fin body to various shapes depending on the swimming conditions in order to produce kinematics that yield high amount of thrust. According to the existing studies [11, 12], a phenomenon called angle-of-attack (figure 1) emerges out of the kinematics to allow thrust generation. The fin interactions with the fluid during oscillation produces a lift force normal to the fin surface, and the angle-of-attack alters the orientation of the lift force component that thrusts the fin body forward [12]. As high angle-of-attack has been observed in many fish species [13] including manta rays, the existing propulsive mechanisms for underwater vehicles that draw inspiration from the oscillatory pectoral fins have been typically designed to allow the kinematics that promote the angle-of-attack.
Several fin design parameters are known to have impacts on the angle-of-attack, such as aspect ratio ($= \text{square of the span length divided by the surface area}$) [14], bending stiffness ($= \text{the force exerted at the fin tip divided by the deflection at the tip}$) [15], and chordwise flexibility [16]. To replicate the angle-of-attack phenomenon, the existing fin designs commonly borrow the values of these parameters from their real counterparts such as aspect ratio of 1.8 observable in the literature [17]. In addition, existing flapping pectoral fin mechanisms commonly feature concepts similar to their real counterpart such as dorsoventrally-flattened airfoil body that can be observed in [18]. These attempts towards replication of the kinematics of the oscillatory pectoral fins have brought many sophistications to their designs, and thus, made them very complicated, e.g. the fins in [18, 19]. Although these fins have been successfully incorporated into underwater vehicles and made significant contributions especially towards their cruising speed, these vehicle have not been able to reached the cruising speed of the vehicles equipped with simpler fin designs, e.g. [15, 20]. For example, MantaDroid [15] with much simpler fins than Aqua Ray [18] could swim 2.26 times faster. This might suggest that a fin design that favours the simplicity and yet improve the fin performance can be a sound replicate for the complicated fin design features embedded to allow mimicking pectoral fins of manta rays.

Amongst the fin mechanisms (e.g. [15, 18, 20–22]), the one that is utilized by MantaDroid exhibits a unique concept of free root chord (figure 2), where the fin has minimal attachment to the body of the vehicle along the root chord. Despite the fact that this is a departure from the reality and the existing fin designs, MantaDroid could cruise at a high speed, which is even greater than the other abovementioned vehicles, e.g. [18, 20]. However, it is unknown whether MantaDroid owes its high cruising speed to its fin’s unique feature of free root chord. Hypothetically, a pectoral fin with a free root chord can yield higher thrust compared to its counterparts that have their root chords attached to the body of underwater vehicles, because the free root chord can allow the fin surface to bend more towards the anterior direction to promote the angle-of-attack further. Previous studies are reviewed in the following to assess the truth of the hypothesis, i.e. whether removing the constraints on the root chord movement can improve the thrust generation.

Extensive studies have reported on the thrust generation of flexible oscillatory pectoral fins of manta rays. In majority of these studies, the movement of the fins are constrained along the root chord, e.g. [23, 24], which replicates the idea of the constrained root chord from the anatomy of pectoral fins of batoid fish species. However, the findings of these studies might not be relevant to the aforementioned hypothesis. In contrast, the findings of the studies on the flexible/rigid foils/panels with pitching motion can be worth looking at because of their free root chord, e.g. [14, 25, 26]. Pitching foils/panels exhibit inclination of the trailing edge towards the anterior direction during pitching motions to produce the angle-of-attack [27]. Zeyghami and Moored [28] studied the thrust generation and propulsive efficiency of a hinged mechanism while undergoing pitching motion. They showed that for a mechanism with one hinge, the thrust can be increased by moving the hinge away from the trailing edge, however, it was at the expense of propulsive efficiency. Moreover, they also demonstrated that for two hinges, more complicated chordwise kinematics can be produced that can result in a gain in both the thrust generation and propulsive efficiency. Other studies on pitching foils/panels, e.g. [14], can show that the chordwise movement contributes to efficient thrust generation. However, these findings cannot be used to assess the truth of the hypothesis because the contribution of the free root chord to the fin surface kinematics is not isolated for the oscillating pectoral fins unlike the pitching foils/panels. In fact, the free root chord incorporates additional kinematic dimension into the spanwise deformation and twist of the pectoral fins compared to the single dimensional chordwise deformation of pitching foils/panels. Overall, it is essential to study if such a simple out-of-the-box departure from the nature (i.e. free root chord) can be
useful for thrust generation and propulsive efficiency of fin mechanisms based on the oscillatory pectoral fins of manta rays.

This paper aims to study the effects of movement constraints at the fin root chord on the thrust generation of oscillatory pectoral fin mechanisms. The movement constraint defines the extent of the anterior part of the root chord that cannot move; i.e. attached to the body of a vehicle. To study the effects of the constraints, twenty fins with different movement constraints were fabricated and tested for thrust generation in a water channel under the free stream condition (0.5 m s\(^{-1}\)). These fins were made up of five variations for the movement constraint that were incorporated into four basic fin designs. The variations were quantified by flexion ratio \(\Delta\) (the length of the anterior part over the root chord length); the range of \(\Delta\) considered was 0 (free root chord), \(\frac{1}{4}\), \(\frac{1}{2}\), \(\frac{3}{4}\), and 1 (full attachment). The basic fins possessed different geometry and flexibility characteristics and were designed based on the fin mechanism in Arastehfar et al [15]. The span length and aspect ratio of all the twenty fins were constant to preserve the hydrodynamic integrity of the experiment.

The paper is organized as follows. The experiment methodology is explained in section 2. Section 3 presents the experimental results followed by discussions. Section 4 concludes the paper.

### 2. Methodology

The thrust generated by twenty different fins and their power consumption were measured in a water channel under a free stream of 0.5 m s\(^{-1}\). To measure the thrust, an ATI Mini 40 IP65 (six-axis force torque sensor) was used. In this experiment, the calibration type used for the sensor was SI-80-4, with sensing ranges of 80 N for \(F_x\) (thrust) and \(F_y\) (lateral force), 240 N for \(F_z\) (lift), and 4 Nm for torque in all directions. The resolution was 0.02 N for \(F_x\) and \(F_y\), 0.04 N for \(F_z\), and 5.0 \(\times\) 10\(^{-4}\) Nm for the torques [29]. The sampling rate used for the data collection was 1 KHz. Each ten samples were averaged by the data acquisition unit accompanied by the sensor to reduce the noise, resulting in 100 data samples per second.

The fins were actuated to oscillate under a wide range of flapping parameters, i.e. stroke frequency \(f\) and stroke amplitude \(A\), as manta rays exhibit various \(f\) and \(A\) to maneuver according to their movement task and environment. This also enabled the production of various fin surface kinematics to study the effects of the movement constraints on the thrust generation across various kinematics. Sixteen sets of flapping parameters (four \(f \times\) four \(A\)) were defined. The range of \(f\) considered was 0.4, 0.6, 0.8 and 1.0 Hz, and the range of \(A\) considered was 40\(^\circ\), 50\(^\circ\), 60\(^\circ\) and 70\(^\circ\), according to [30]. These flapping parameters resulted in sixteen chord Reynolds number (1) ranging from 2.2 \(\times\) 10\(^4\) to 8.2 \(\times\) 10\(^4\).

\[c\text{Re} = V \cdot c/v\]  

(1)

where, \(c\) is the mean chord length, \(\nu\) is the kinematic viscosity of water at 25 \(^\circ\)C, and \(V\) is the fin tip average velocity given by \(V = 4 \cdot L \cdot f \cdot \sin(A \cdot \pi/360)\), \(L\) is the fin span length (figure 2).

A complete run of the experiment involved ten oscillations per set of flapping parameters. For a fin configuration, the thrust values measured during the oscillations were averaged to give the average thrust \((T)\) that the fin generated under the range of the chord Reynolds numbers. A Hitec HS-5646WP servomotor was used to oscillate the fins under the flapping parameters to generate the thrust. The maximum torque generated by the servomotor was 1.27 Nm at 7.4 V, and the maximum speed was 330\(^\circ\) s\(^{-1}\).

#### 2.1. Fin design

The basic pectoral fin design was made up of two main components: flexible fin film and leading edge spar (figure 3). The flexible fin films were made of polyvinyl chloride (PVC) sheets. A total of two thickness variants (0.1 and 0.3 mm) of PVC sheets were considered for this experiment to vary the degree of fin surface flexibility. The leading edge spar was fabricated from three-dimensional (3D) printing process and the material used for the print was polylactic acid (PLA) filament (Young’s modulus of 1.514 GPa, obtained via tensile testing). The 3D printer used was the Makerbot replicator 2. The thickness of the leading edge spar tapered from 4 mm at the root to 1 mm at the tip. An offset in the form of a profile recess (figure 3) was incorporated on the leading edge joint to mount the fin onto the servo arm. In addition, for the leading edge, two sweep angle variations (30\(^\circ\) and 40\(^\circ\)) were considered to vary the geometry of the fins. The reason for deciding on these two variations were to simulate the sweep angle of an actual manta ray as close as possible, which mainly ranges from 30\(^\circ\) to 40\(^\circ\). The two variations of the fin film and the two variations of the sweep angle made up the four basic fin designs. The fin with sweep angle 40\(^\circ\) and thickness of 0.3 mm is the exact replica of the fin that MantaDroid is currently using. The actuator and the drive mechanism in the experiments of this study are exactly the same as that of MantaDroid.

The movement of the basic fins were constrained at the anterior part of their root chord. The movement constraints were quantified by flexion ratio \(\Delta\) that is the length of the anterior part over the length of the root chord. Five variations of \(\Delta\) (figure 3) were incorporated into the four basic fin designs resulting in twenty unique fins. The two extreme variations were 0 indicating no constraint (i.e. free root chord) and 1 indicating fully-constrained root chord (i.e. the entire fin root chord is attached to the body of a vehicle). The other three variations were for partially-constrained root chord, where one quarter (\(\Delta = \frac{1}{4}\)),...
half ($\Delta = \frac{1}{2}$), and three quarter ($\Delta = \frac{3}{4}$) of the root chord were constrained. These constraints were introduced by attaching a rigid bar to the anterior part of the root chord (figure 3). The length of the rigid bars was defined by $\Delta$. These bars were merged together with the leading edge as an extension from the joint, and were 3D-printed together with the leading edge spar as one complete piece.

The fins were completed by joining the PVC sheets to the leading edge spar and the bar by using contact adhesive from Selleys Kwikgrip. In order to provide a fair comparison among the various fins, the span length and the surface area were made to remain constant at 0.24 m and 0.0264 m² respectively.

Given the sinusoidal flapping motions implemented by the servomotor, the kinematic model of the fin surface along the transverse axis ($z$-axis in this study, figure 3) is estimated by (2), according to [31].

$$z = y \cdot (a \cdot \sin(2\pi \cdot f \cdot t \cdot -\theta) + b)$$

where, $z$ of a point is estimated by using its distance ($y$, figure 3) from the root chord and its instantaneous flapping angle ($2\pi ft - \theta$); $\theta$ is the phase lag between the angular position of the servomotor and that of the point. A linear approximation is made to take into account the fin flexibility according to [31]; $a$ is introduced as a factor defining the maximum transversal travelling distance of the point, and $b$ is introduced to define the asymmetry in the deviation from the neutral position ($z = 0$) of the point along the transverse axis.

2.2. Experiment setup

The experiment was carried out at a water channel. The tank in the water channel (figure 4) measures 2.20 m (length) × 0.75 m (width) × 1.18 m (height). Water was filled to a depth of 0.90 m during the experiment, and the fin specimens were placed in water at a depth of 0.50 m and spaced 0.40 m from the walls of the tank. This placement position ensures that the fins are submerged at a depth of 4.5 mean chord lengths in order to minimize the surface effect. In addition, spacing the fin 3.5 mean chord lengths from the walls was to allow mitigation of the wall effect. An aluminium rod (figure 4) was used to secure the fin and the servomotor assembly. The force torque sensor was located at the upper section of the rod as it was not waterproof. The experiments were done under a free stream condition. A centrifugal pump generated the circulating water to produce the flow velocity of 0.5 m s$^{-1}$.

2.3. Evaluation criteria

Thrust is one of the important criteria to evaluate the fin performance as it determines how quickly the robot body can accelerate and how fast it can swim [4, 24]. The thrust $T$ obtained for each fin was nondimensionalized to coefficient of thrust ($C_T$) by applying (3)

$$C_T = \frac{T}{0.5 \cdot L \cdot c \cdot \rho \cdot U^2}$$

where $S$ is the span length (0.24 m), $\rho$ is the density of water (1000 kg m$^{-3}$), and $U$ is the free stream velocity (0.5 m s$^{-1}$).

Another important criterion is the Froude propulsive efficiency (4) that indicates the efficiency of the conversion of electrical power input into the thrust generated

$$\eta_P = \frac{T \cdot U}{P}$$

where $P$ is the power input to the fluid. $P$ was obtained by taking the difference between the average powers supplied to the actuator in water and air, to normalize out the power supplied to move the fin.

2.4. Repeatability and reliability

To ensure the repeatability of the experiment, the experiment was repeated five times for ten randomly selected fin designs. For each fin, the matrix of the Pearson correlation coefficients [32] was applied to the five measurements, resulting in ten $5 \times 5$ matrices. The correlation coefficient was averaged across the elements in the upper triangular part of the matrices, and across ten fins. Note that only the elements found
in the upper triangular part was averaged because of the symmetrical nature of the matrices. The computed Pearson correlation coefficient was 0.98 ± 0.08. The high correlation coefficient shows that the experiment is highly repeatable. Moreover, for the measurement of the thrust values, for each fin design, the standard deviation (SD) was calculated for the T values corresponding to a set of the flapping parameters. The SD ranged from 0.01 to 0.02, and it was averagely less than 4.7% of T. This small SD shows that the measurement error was small as well, which can be attributed to the high signal-to-noise ratio of the sensor (near zero distortion) [29].

3. Results and discussion

CT values of the fins are shown in figure 5(a). Each solid/dashed line represents CT of a basic fin design, e.g. the solid line on the left graph, shows CT of the fin with sweep angle of 30° and surface thickness of 0.1 mm. CT of the fins with sweep angles 30° and 40° are shown in separate graphs for clearer illustrations. All the changes in CT from Δ = 0 to Δ = 1 are significant and the inequality relations observable between these CT are supported by the results of statistical hypothesis tests via one way paired t-test, at significance level of 0.05 (see appendix A). As can be seen in the graphs, for each basic fin design, there are two distinctive parts that can be partitioned by the vertical line at Δ = 1/4. The left side of Δ = 1/4 shows that for all the basic fins, imposing the constraint on the fins with free root chord yielded reduction in the amount of thrust generated. While on the right side after Δ = 1/2, the thrust continuously increased and reached its maximum for full constraint (Δ = 1). These two observations can indicate that the oscillatory pectoral fins benefit more from the extremes of the constraints, either minimal constraints or full constraints, to generate high thrusts. Moreover, a visual comparison between the fins with different sweep angle can show that the sweep angle might not have significant effects on the amount of thrust generated in the process which is in agreement with the results of [15].

Referring to figure 5(a) fin with freed root chord can be more efficient while not losing a significant thrust capability. For example, for fins with surface thickness of 0.1 mm, efficiency was increased by factor of 1.4, while CT slightly decreased from 0.15 to 0.13. In addition, for fins with surface thickness of 0.3 mm, efficiency was increased by factor of 1.35, while the change in CT was insignificant. Therefore, a fin can be both powerful and efficient if the root chord is freed.

From the graphs of the fins of different thickness in figure 5(a) (comparing the dashed lines with the solid lines), it can be seen that the constraint and fin thickness have joint effects on CT. These effects are different to the left and right sides of Δ = 1/4. On the left side, the increase in the fin thickness resulted in improved CT, and the amount of the improvement was increased by decreasing Δ. This might be contradicting as the thicker fins can reduce the angle-of-attack because they are stiffer. In fact, slight downgrades of the angle-of-attack was observable in the thicker fins. However, further investigation showed that the thicker fins with Δ < 1/4 were able to withstand the fluid more strongly during the flapping motions which caused displacement of higher amount of water to generate greater lift force. As observed, the greater lift compensated for the slight downgrade of the angle-of-attack, and the overall result was higher amounts of thrust. For Δ > 1/4, unlike the left side, the thicker fins generated less amount of thrust, and the difference in the amount of thrust became more significant for greater Δ. In this case, while both thick and thin fins could generate comparable lift force, the latter allowed relatively higher angle-of-attacks so as to generate higher amount of thrust. Therefore, for generating higher amounts of thrust, the oscillatory pectoral fins with free root chord require relatively stiffer surfaces, and the fins with fully constrained root chord need relatively less stiff surfaces.

ηp is illustrated in figure 5(b) (see appendix A for more details about the data). It is clear that the basic fins became less efficient by increasing the constraint on the movement of the root chords. From the observations, the added constraints, by limiting the fins’ deformation, reduced the angle-of-attack, which resulted in less efficient conversion of the lift force into thrust. Therefore, the reduction of the constraints on the root chord movement can yield higher efficiency of conversion of the lift force into the thrust. From figure 5, the higher efficiency could only result in higher thrust for Δ < 1/2. In this region, although the fins with less constrained root chord generated lower lift force, the higher efficiency, which was due to the promoted angle-of-attack, could lead to higher thrust despite of the lower lift force. In contrast, from Δ = 1/4 to Δ = 1, the efficiency could not lead to higher thrust from the lower lift force. Moreover, the thinner fins were more efficient than their thicker counterparts. From the results, the thinner fins converted the lift force into the thrust more effectively because of producing higher angle-of-attack, which can be attributed to their higher ability to bend. Therefore, improving the fin flexibility by reducing the fin surface thickness can yield higher efficiency of conversion of the lift force into the thrust. However, this does not necessarily mean that higher amounts of thrust can be generated because the more flexible fins can generate relatively lower lift force. Similar to the root chord constraints, here it is a matter of whether the promoted angle-of-attack can compensate for the lower lift generated; which is the case for Δ greater than 1/4 (figure 5(a)).

Overall, it is shown that freeing the root chord of a fin design can affect the fin’s overall ability to passively flex and displace water. This ability affects the
fin performance on both thrust and efficiency. Thus, choosing the concept of free root chord requires other actions to be taken so as to keep up with the performance of the original fin design. For example, to improve the efficiency of the fin with sweep angle of 40° and the surface thickness of 0.1 mm (design A in the graphs of figure 5), it is best to free the root chord (design B). However, the high efficiency of design B is at the expense of thrust. To compromise, increasing the surface thickness (design C) can help improve the thrust with a drop in the efficiency. As can be seen in figure 5, the thrust of the new fin design C can be comparable to that of the original fin, while its efficiency is higher. Therefore, freeing the root chord is a design problem with conflicting performance parameters. Providing that the other design choices are revisited carefully, the concept of free root chord can be significantly beneficial to the performance of the fins.

The above-mentioned results can be investigated thoroughly through a study on the thrust generation process of the fins. While a fin flaps, it replaces an amount of water. In this process, the water exerts a reaction force (lift force) which is normal to the fin surface. During this fin-water interaction, fin surface exhibits kinematics that define the magnitude of the lift force and its orientation. To generate a high thrust, it is important that the kinematics increase the magnitude of the lift force and direct it towards the swimming direction as much as possible. In addition, while the fin kinematics manipulate the direction of the lift force, the lift produces the force components that are normal to the swimming direction, i.e. vertical and lateral forces. These forces can negatively affect the swimming performance of underwater vehicles by introducing unwanted movements. For example, the vertical force is naturally alternating and moves the body of the underwater vehicles up and down during forward swimming. Therefore, in the following, to examine the performance of the fins with the different root chord constraints, we analyse the components of the lift force, i.e. thrust force, vertical force, and lateral force, and the bending direction of the fin surface that has two components, i.e. angle of attack (fin bending towards the anterior direction), and the lateral rotation (fin bending towards the lateral direction defined by the left-right axis of fish bodies).

For further analysis, only the root chord constraints with distinct performances were considered, i.e. free root chord that generated high thrusts with the highest efficiency, Δ of 1/4 that generated the least thrust, and fully constrained root chord that generated the highest thrust with the lowest efficiency. Figure 6 summarizes the results of the analyses for the basic fin design with sweep angle of 40° and thickness of 0.1 mm (namely F40.1) and flapping at stroke frequency of 1 Hz and stroke amplitude of 70°. The numbers are the descriptive values of the measurements, e.g. mean and root-mean-square (RMS). As can be seen from the first row in figure 6, the fins with fully constrained root chord could generate the highest lift force that could be contributed to the limitation on the fins’ surface movement brought by the constraints that improved the fins’ ability to withstand the water resistance during the flapping. The mean lift force of F40.1 with Δ = 1 was about 22% higher than that of F40.1 with free root chord. However, the thrust generated by the fully constrained F40.1 (second row in figure 6) were only 13% higher than that generated by its counterpart with the free root chord. Such deficiency of the fully constrained fins can be attributed to the bending behaviour of these fins. Referring to the last two rows in figure 6, these fins produced smaller angle-of-attack and directed the lift force towards the body. Such orientation of the force could significantly reduce the amount of thrust. Referring to figure 1, the angle-of-attack is estimated by computing the angle between the measured lift force that is normal to the fin surface and the measured vertical force that is normal to the flow. The angle of attack was obtained throughout the flapping motion at the frequency of 100 Hz.

In contrast, the fins with free root chord, although generated lower lift force, could effectively direct it towards the swimming direction both in the frontal and sagittal planes, resulting in keeping the thrust at high values. Moreover, a comparison between the fins
of $\Delta = 0$ and $\Delta = \frac{1}{4}$ can show that despite generating almost equal mean lift force (very small difference of 4% for F40.1), the mean thrust by $\Delta = \frac{1}{4}$ was significantly reduced (14% for F40.1). This can also be explained through a comparison of the fin kinematics produced. Referring to the last two rows in figure 6, the fins of $\Delta = \frac{1}{4}$ produced relatively smaller angle of attack and bent towards the lateral direction, which could negatively affect the amount of thrust generated. Overall, it can be said that freeing the root chord can promote the angle-of-attack. Besides, by freeing the root chord, the fin surface bends around the left-right axis (e.g. negligible average offset of $2^\circ$ for F40.1), directing the lift force effectively towards the swimming direction in the frontal plane so as to increase the amount of thrust. These can also explain the higher efficiency of the fins with free root chord because the smaller lift force can indicate lower power consumption, and the more effective thrust generation can show that the power consumed were converted into thrust more effectively.

Moreover, referring to the vertical forces (the third row in figure 6), these forces are alternating and symmetrical about the anterior-posterior axis. Thus, they may not cause drift in the vertical direction. However, they cause unwanted up-down movement of the vehicles along the swimming path. As is clear, the higher lift force generated by the fins with $\Delta = 1$ resulted in much higher (around 28% for RMS values of F40.1) vertical forces, which can negatively affect the swimming performance of underwater vehicles. Furthermore, the lateral force (the fourth row in figure 6) seem to be less pragmatic as they cancel out during symmetrical flapping. Nevertheless, in the case of asymmetrical flapping that might be required depending on the swimming condition, e.g. for turning, it causes lateral drift that can be slightly more significant for the fully constrained fins. All the findings based on the results in figure 6 can be applicable to all sets of kinematic parameters and the basic fin designs considered in this study.

The concept of the disengaged root chord to some extent exists in the nature especially for the animal species that fly at high flapping frequencies, such as insects. For example, the flapping frequency for insects with synchronous flight muscles typically ranges from 5 to 200 hertz (Hz), and for those with asynchronous flight muscles, wing beat frequency may exceed 1 kHz [33]. However, this range is well beyond the flapping frequency of the species having their root chord attached to their body; about less than 5 Hz [34, 35]. From our experiences with the free root chord fins on the MantaDroid robot (https://news.nus.edu.sg/press-releases/NUS-robotic-manta-ray), it can be said that these fins, with the same actuators and
under similar swimming conditions, can allow achieving higher flapping frequencies compared to the fins with the constrained root chord. For example, for the fins with $\Delta = 1$ at flapping frequency of 1.2 Hz, the servomotors could not exactly follow the flapping trajectories and missed the rotation steps, whereas, for the fins with $\Delta = 0$, the flapping trajectories were followed without missing steps. For example, referring to the angle-of-attacks in figure 6, at frequency of 1 Hz where both fins (i.e. $\Delta = 0$ and $\Delta = 1$) could follow the flapping trajectory, the fins with free root chord coped with less resistance from the fluid (implied by the less lift force) because they inclined more towards the anterior direction. This discussion leads to a question as to whether reducing the constraints of the root chord movements can enable flapping at higher frequencies, which require further studies to answer.

For the variations of the stroke frequency ($f$) and stroke amplitude ($A$) considered in this study, for a fin flapping at a certain $A$, an increase in $f$ resulted in an increase in both coefficient of thrust and propulsive efficiency. Besides, at a certain $f$, the same was observed for an increase in $A$. These findings can demonstrate significant influence of $A$ and $f$ on both thrust and efficiency, which is in agreement with the findings of hydrodynamic thrust in the literature [36]. For $\Delta$, we used one way paired t-tests (see appendix A for more details on the statistical hypothesis test) to test if thrust is improved after adding more constraints to the movement of root chord. Alternative hypothesis stated that the mean of the differences of $\Delta$, an increase in $f$ resulted in an increase in both coefficient of thrust and propulsive efficiency. Besides, at a certain $f$, the same was observed for an increase in $A$. The null hypothesis was rejected for $\Delta$ from $\frac{1}{4}$ to 1, showing that an improvement in $C_T$ can be expected for each set of flapping parameters. For $\Delta$ from 0 to $\frac{1}{4}$, we failed to reject the null hypothesis at significance level of 0.05, implying that a reduction in $C_T$ can be expected. Similar test on the efficiency found strong evidence to reject the increase of the mean differences at significance level of 0.05, showing that for each set of flapping parameters, the efficiency decreases after increasing $\Delta$. According to the above, it can be said that the findings of this study can be valid for the variations of $f$ and $A$ considered in this study.

As shown earlier for free root chord, the fin thickness alteration had different impacts on $C_T$ and $\eta_P$, where a change in the thickness could have positive impacts on one, and at the same time, negative impacts on the other. Our future work will focus on the design of fin surfaces with varied thickness that can outperform the fins with uniform thickness by improving both $C_T$ and $\eta_P$. For this, identification of the regions of the fin surface that could be responsible more for production of the lift force and angle-of-attack could be the key. This can allow defining the thickness specifically for each region so as to simultaneously boost the lift force and promote the angle-of-attack.

In this paper, we looked at the oscillatory pectoral fins of manta rays from the design perspective, given the technological limitations we have in terms of design implementation and many unknowns about these fins that are yet to be uncovered. We investigated if simple modifications (e.g. freeing the root chord in this study) that are departure from the nature can help us give a boost to the performance of the fin designs in addition to the inspirations drawn from the actual fins. Based on our experiments with MantaDroid, we observed greater swimming stability and smoother swimming bough by the fins with free root chord. However, freeing the root chord comes with consequences too. The major concern is the effects of the loads, resulting from the interactions between the fin surface and the fluid, on the actuators. These loads, in fins with free root chord, are absorbed by the bearings of the actuator, which reduces its lifetime. For larger fins, extra load bearings are required to hold the fins in place so as to prevent unwanted vibrations. In contrast, for the fin designs with root chord attached to the body of the vehicle, this load is distributed along the root chord and absorbed by the body to a great extent.

4. Conclusions

The kinematics that the oscillatory pectoral fin designs exhibit during the flapping motion define the amount of thrust they can generate and the efficiency of thrust generation. It was shown that the constraint on the movement of the root chord of these fins, which is also appeared in the nature as the attachment to the body of manta rays, can be influential to the fin kinematics, and thus, thrust generation. By reducing the constraint to minimum (i.e. free root chord), the fins’ efficiency was significantly increased because of promoting the angle-of-attack. However, it was at the expense of thrust because the fins with free root chord could relatively produce smaller lift force. Further investigation showed that incorporation of the concept of the free root chord could be more effective at boosting the fins’ performance if it is coupled with increasing the fins’ ability to withstand water resistance during flapping, for example, by increasing the fin thickness. Such a fin design, in comparison with the fins with fully constrained root chord, could generate comparable thrust with higher efficiency. Overall, the concept of free root chord can allow considerable improvement in the performance of oscillatory pectoral fin designs so as to produce the fins that are both powerful and efficient for thrust generation.

Furthermore, it was demonstrated that not only was the concept of free root chord effective at improving the fins’ performance but also it could have positive effects on the swimming performance of underwater vehicles. The fins with free root chord
more successfully directed the lift force towards the swimming direction, which resulted in a remarkably smaller components of the lift force that are normal to forward swimming direction, e.g. vertical and lateral forces. As illustrated, the reduction of the vertical and lateral forces could damp the unwanted movements of underwater vehicle; for example, knowing that the alternating vertical force causes unwanted up/down movement during forward swimming, producing smaller vertical force is desirable to reduce this unwanted movement.

Declaration of conflicting interests

The authors declare that there is no conflict of interest.

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Appendix A. Box charts

Figure A illustrates the box charts of $\Delta T$ and $\eta P$, respectively, including the mean values, median lines, standard deviations, and interquartile ranges. As can be seen, the medians are almost in the middle of the boxes, and the whiskers are about the same size on both sides of the boxes, which may imply that the data are normally distributed. To reaffirm the normality of the distributions, Shapiro-Wilk test was used at confidence level of 0.05. Strong evidence was found to support that the data of each chart box was significantly drawn from normally distributed populations. In addition, for each basic fin design, the interquartile ranges and the standard deviations vary a little (less than $\approx 10\%$) between the variations of $\Delta$. The above can suggest that for a basic fin design, the data points of each $\Delta$ were drawn from normal distributions with similar variances. Given the normality of the distributions, one way paired $t$-test was used to test the hypothesis that for one basic fin design, when increasing $\Delta$ from one variation to the next one (i.e. from 0 to $\frac{1}{4}$, $\frac{1}{4}$ to $\frac{1}{2}$, $\frac{1}{2}$ to $\frac{3}{4}$, and $\frac{3}{4}$ to 1):

(a) The mean difference between $\Delta T$ produced under the same set of flapping parameters is greater than 0, implying an increase in the coefficient of thrust

(b) The mean difference between $\eta P$ under the same set of flapping parameters is less than 0, implying a decrease in the efficiency

The null hypotheses stood for the differences in the other direction. At confidence level of 0.05, strong evidence was found to reject all the null hypotheses, except for $\Delta T$ when increasing $\Delta$ from 0 to $\frac{1}{4}$. According to the test results, it can be inferred that for a set of flapping parameters, increasing the constraint at the root chord from 0 to $\frac{1}{4}$ reduces $\Delta T$, while further increases from $\frac{1}{4}$ to $\frac{1}{2}$ result in an increase in $\Delta T$. In addition, the efficiency decreases with imposing more constraints.

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