Journal of Engineering Science and Technology
Vol. 12, No. 1 (2017) 001 - 014

INVESTIGATING PECTORAL SHAPES AND LOCOMOTIVE STRATEGIES FOR CONCEPTUAL DESIGNING BIO-INSPIRED ROBOTIC FISH

A. I. MAINONG[1], A. F. AYOB[1,]*, M. R. ARSHAD[2]

[1]School of Ocean Engineering, Universiti Malaysia Terengganu, 21030 Kuala Terengganu, Terengganu Malaysia
[2]School of Electrical and Electronic Engineering, Universiti Sains Malaysia, 14300 Nibong Tebal, Pulau Pinang, Malaysia
*Corresponding Author: ahmad.faisal@umt.edu.my

Abstract

This paper describes the performance analysis of a conceptual bio-inspired robotic fish design, which is based on the morphology similar to the boxfish (*Ostracion melagris*). The robotic fish prototype is driven by three micro servos; two on the pectoral fins, and one on the caudal fin. Two electronic rapid prototyping boards were employed; one for the movement of robotic fish, and one for the force sensors measurements. The robotic fish were built using fused deposition modeling (FDM), more popularly known as the 3D printing method. Several designs of pectoral fins (rectangular, triangular and quarter-ellipse) with unchanging the value of aspect ratio (AR) employed to measure the performance of the prototype robotic fish in terms of hydrodynamics, thrust and maneuvering characteristics. The analysis of the unmanned robotic system performance is made experimentally and the results show that the proposed bio-inspired robotic prototype opens up the possibility of design optimization research for future work.

Keywords: bio-inspired robotics, 3D printing, boxfish, aspect ratio, STD.

1. Introduction

Fish are efficient swimmers and have excellent manoeuvrability [1-3]. Muller et al. [4] have shown that the hydrodynamic efficiency in the swimming performance of fish could be as high as 90%. Thus, researchers are interested in designing the underwater vehicle by adapting the natural shape inspired by real fish. Fukuoka et al. [5] stated that the traditional robot design could be improved

Nomenclatures

A	Surface area of pectoral fin, mm^2
f	Frequency, Hz
Fr	Froude number
g	Gravity, m/s^2
L	Length of boxfish robot, m
l	Length of pectoral fin, m
Re	Reynolds number
s	Distance, m
St	Strouhal Number
t	Time travel in second, s
U	Body velocity of the boxfish robot, m/s
V	Velocity of the boxfish robot, m/s
w	Width of pectoral fin, mm

Greek Symbols

μ	Dynamic viscosity, kg/ms
v	Kinematic viscosity, m^2/s
ρ	Density, kg/m^3

Abbreviations

ABS	Acrylonitrile Butadiene Styrene
AR	Aspect ratio
FDM	Fused deposition modeling
FSR	Force Sensitive Resistor
STD	Steady Turning Diameter

through the adaptation of animal motion. As far as manoeuvring, the adaptation of a bio-inspired concept is important due to fishes' efficiency in their movements while handling dynamic spontaneous motions in underwater environments, such as current, turbulence or fine areas such as coral and reefs [6].

A study of the swimming mode of fish has done by Lindsey's [7] classification where Ostraciform is defined as the one swimming mode where only the fins are oscillated while the rest of the main body does not move. The paired fins are mainly used to propel compared to the caudal fin. The bodies on these fishes are often inflexible. Figure 1 shows an example of a fish that uses only its fins to propel itself [7, 8].

Boxfish is a great example of the Ostraciform propulsion mode. Usually, the Boxfish's swimming mode combines the pectoral fins with the anal and dorsal fins to move. The caudal fin action is used as a rudder to control their manoeuvrability [8]. Previous study [1] used fins with different shapes and stiffness to study the relationship between vortex formation and thrust performance. It is believed the stiffness of the fin increases the thrust produced by the robot fish [9].

Fig. 1. Yellow boxfish mainly live in reefs and can only swim slowly [6].

Fish generate fluid-dynamic forces by flapping flexible appendages, such as fins. The motions of this structure can be resolved into two forces; vertical forces that balance he weight and horizontal forces that provide thrust for forward motion [10]. In oscillatory motions, there are two modes of motions of pectoral fin: rowing and flapping. The rowing mode of motion is a drag-based type of motion that generates thrust forces by anterior and posterior motions of fins [11]. The flapping mode of motion is a lift-based type of motion that generates thrust forces through up and down motions [9, 11]. In a lift-based model, oscillating motions are generated by flapping the fins up and down in an area almost perpendicular to the main axis of the fish body.

Wing platform shapes (pectoral fins), in particular, have commonly been associated with locomotors performance during steady swimming because of the higher induced drag associated with the low aspect ratio [10]. Low aspect ratios generally have blunter tips and thus may lose more circulation in that region [12]. Therefore, high aspect ratios of pectoral fins generate more force per area and perform more efficiently than low aspect ratio pectoral fins.

The shape of a propulsor the Reynolds Number and its flow deformation are important factors in evaluating thrust performance and the distribution of spanwise flow. When dealing with a low Reynolds Number case, spanwise flow is not as strong as a high Reynolds Number case [9]. The fundamental difference in the thrust generation mechanisms between lift-based and drag-based propulsion can be better understood by examining vortex formation.

In this paper, a concept underwater robot design that bears the resemblance of a boxfish (*Ostracion melagris*) is proposed. In the proposed design, three simple shapes (rectangle, triangle and quarter-ellipse) were considered as the pectoral fin of the boxfish. The area covered by each of the pectoral fins and its base length were kept constant while the performance of each shape was investigated. Three case studies were presented in order to investigate the best locomotion strategies of the proposed underwater robot design; propelled by pectoral fins, propelled by caudal fin and propelled by both sets of fins. The results of the three performance indicators of the proposed design were presented (i.e., thrust, hydrodynamics and steady turning diameter).

2. Mechanical Design

The prototype of robotic fish was designed based on boxfish morphology and a focus on the body as well as choosing the appropriate fin shape to make sure it can produce a good performance in the manoeuvring aspect. Generally, the length, breadth and height of the robotic fish are 165mm, 67mm and 60mm, respectively, as shown in Fig. 2. The dimensions of the boxfish was printed using the Acrylonitrile Butadiene Styrene (ABS) by a 3D printer is shown below.

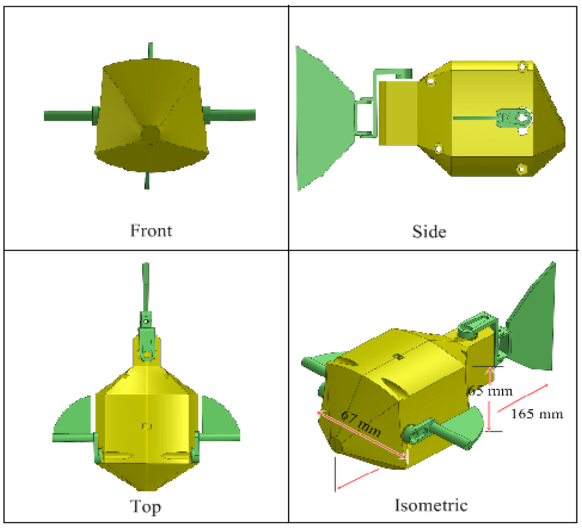


Fig. 2. Dimensions of the robotic prototype.

The body of robotic fish is made of a two part module where the first part consists of two pectoral fins and the second part provides a joint caudal fin (Fig. 3).

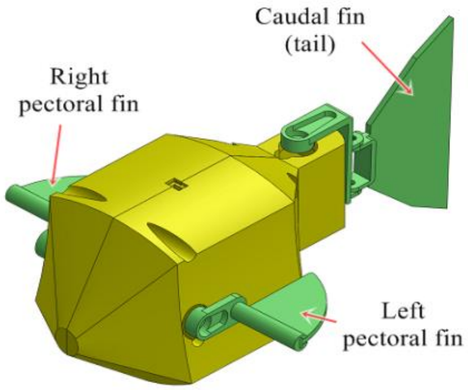


Fig. 3. Pectoral and caudal fin of the robotic fish.

To investigate the hydrodynamic performance of fins, different bending characteristics are considered for each pectoral fin by a fixed the surface area, width and aspect ratio. Figure 4 shows the width and length of pectoral prototype using on robotic fish. Table 1 shows the characteristics of the both types pectoral fin used in this study with a fixed area and base/length to calculate the AR as shown in Eq. (1). To calculate the surface area for every fin, quarter-ellipse by using Eq. (2), rectangle by Eq. (3) and triangle by Eq. (4).

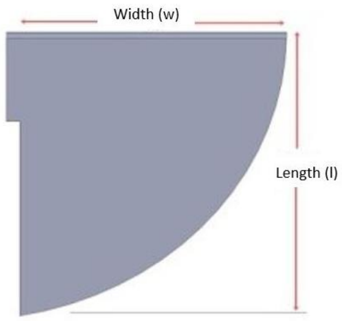


Fig. 4. Width and length for pectoral fin.

$$AR = \frac{w^2}{A} \tag{1}$$

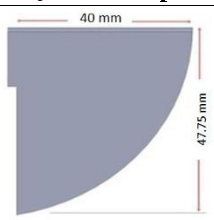
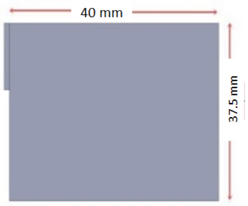
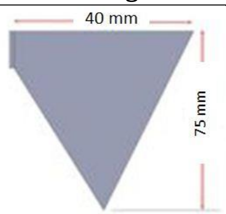
$$A = \frac{\pi w l}{4} \tag{2}$$

$$A = wl \tag{3}$$

$$A = \frac{1}{2} wl \tag{4}$$

where w is the width of the pectoral fin, l is length of pectoral fin and A is the surface area of pectoral fin.

Table 1. Characteristics of pectoral fin.

Characteristics		
Surface Area (*A*)	1500 mm^2	
Witdh (*w*)	40 mm	
Aspect Ratio (AR)	1.067	
Quarter-ellipse	**Rectangle**	**Triangle**
		

This study was conducted on the effect of different pectoral shapes on manoeuvring motion of the robotic fish and a fixed caudal fin (Fig. 5). The conceptual design of the caudal fin referred to the previous work conducted by Park et al. [13] and it was found that a delta-shaped fin has the ability to produce a good thrust.

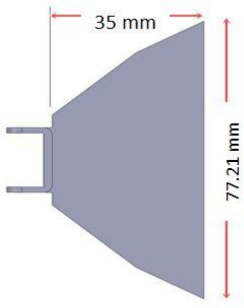


Fig. 5. Caudal fin of the robotic fish.

2.1. Locomotion control

The robot was controlled by ATmega328 as a microcontroller (Arduino Uno). Arduino Uno is selected as the microcontroller to control the robotic fish which corresponds to the written programs in 5V operating voltage. By using Arduino 1.5.2 software, the coding for servo movements was uploaded to the board; Fig. 6 shows the mechanical configuration of the robotic prototype. In this configuration, there are four different space placed on the body of robotic fish. The function of this all spaces is to control the buoyancy and stability of robotic fish. It is also the location where the added weight will be placed.

The locomotors for Ostraciform forward movement only used the pectoral and caudal fins as a medium to produce thrust. The robotic fish used three units of servo as a three main actuators to propel the robotic fish in an underwater environment. Two servos are acts as pectoral fin which is provide thrust to the forward movement of robotic fish. To control caudal fin, one unit servo was attached on the robotic fish. In this paper, the locomotion controls of the robotic fish was divided into three cases and are illustrated in Figs. 7(a), (b) and (c) by involving three different shapes of pectoral fins. For Case A, the boxfish robot move forward by only the pectoral fin. Then Case B, movement by only the caudal fin and Case C movement by both pectoral and caudal fin.

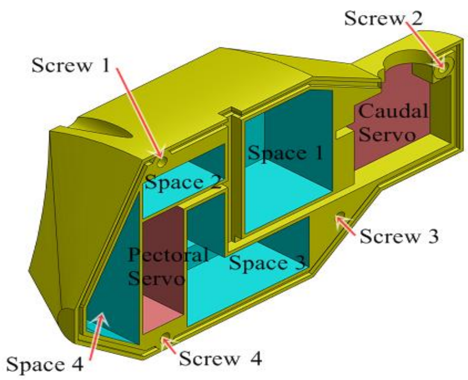
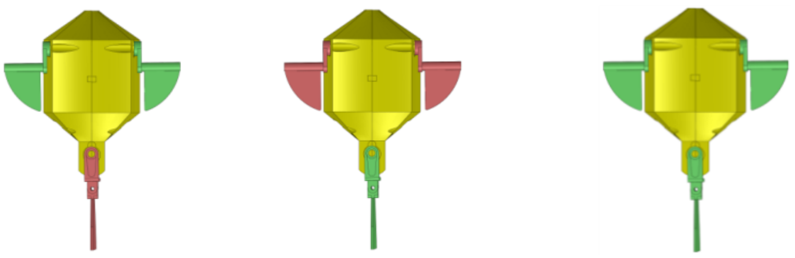


Fig. 6. Mechanical configuration of the robotic fish.



(a) Pectoral fins **(b) Caudal fin** **(c) Caudal and pectoral fins**

Fig. 7. Locomotion cases of the boxfish for forward movement.

2.2. Velocity and thrust measurement

The distance tracking and time travelled by the robotic fish were collected as shown in Fig. 8. Using the fixed frequency (*f* = 2.5 Hz), the velocity of robotic fish was calculated by the following formula:

$$V = \frac{s}{t} \tag{5}$$

where *s* is the distance and *t* is the time.

In laboratory works, a tank consists of two monitoring controllers (computers) are set up. The first computer is used to monitor the movement configurations of robotic fish and the second computer is used to collect the thrust data from Force Sensitive Resistor (FSR). In each experiment, different shapes of pectoral fins are attached to the main body while maintaining a delta-shaped caudal fin. The robotic fish is tested under the control conditions of calm water in a small tank to reduce external factors that may affect the parameters involved.

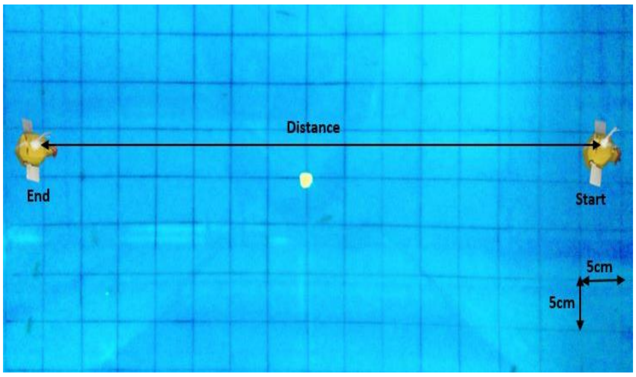


Fig. 8. Velocity measurement method for the boxfish robot.

2.3. Reynolds, Strouhal, and Froude numbers

The Reynolds Number, Re - is a dimensional number and is defined as the ration forces to viscous forces. The Reynolds Number, refer Eq. (6), was introduced by Osborn Reynolds to determine types of flow.

$$\text{Re} = \frac{\rho VL}{\mu} = \frac{VL}{\nu} \tag{6}$$

where V is the forward velocity of the boxfish robot in m/s, L is length of the body in m, μ is dynamic viscosity of the fluid (1×10^{-3} N.s/m^2), ν is kinematic viscosity at temperature 20^{o}C (1×10^{-6} m^2/s) and ρ is fluid density (1000 kg/m^3).

Strouhal Number, St, is a non-dimensional measure of frequency for periodic flows. It represents a measure of the ratio of inertial forces due to the unsteadiness of the flow or local acceleration to the inertial forces due to changes in velocity from one point to the other in the flow field.

$$\text{St} = \frac{fL}{V} \tag{7}$$

where f is the frequency of flapping fin, L is length of the body and V is forward velocity of the boxfish robot.

Froude Number, Fr - is a dimensionless number of the ratio of a characteristic velocity to a gravitational wave velocity. It may be defined as a ratio of inertia to the gravitational forces in a liquid. It is a dimensionless quantity used to indicate the relationship between gravity and fluid motion. Fr is used to determine the resistance to a body flowing through a fluid at a specific velocity creates.

$$\text{Fr} = \frac{U}{\sqrt{gL}} \tag{8}$$

where U is body velocity, g is gravitational force and L is length of the boxfish.

2.4. Steady turning diameter

STD was measured by turning the fish robot 360 degrees by maintaining the frequency. The bottom of the tank was square (5cm x 5cm) to measures the diameter of turning by robot fish. STD movements get from the turn left measurement whereas only the right pectoral fin move and the left pectoral fin was fixed with perpendicular angel of body. The camera was records the movements of robot fish in circle as shown in Fig. 9.

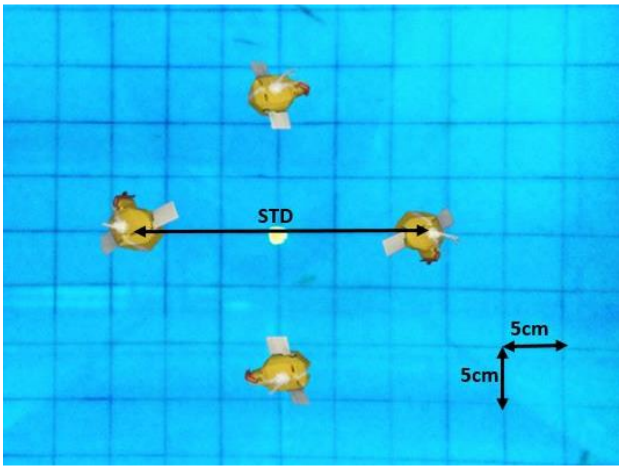


Fig. 9. STD measurement method.

3. Result and Discussion

3.1. Thrust and speed

Forward thrust data was recorded by an FSR sensor in multiple locomotion cases of robotic fish. As shown in Figs. 10 and 11 forward thrust (Fig. 10) and speed data (Fig. 11) were collected in Case A where only the pectoral fin is moved; in Case B by using a caudal fin; Case C used a combination of pectoral and caudal fins to produce thrust. Thrust production from a combination of caudal and pectoral fins was recorded as the highest amount of thrust forward for the robot fish, especially with a quarter-ellipse fin shape. It is also gave the highest speed for robot fish. In case A, the quarter-ellipse is a good propulsor followed by rectangle and triangle because the quarter-ellipse pectoral fin has the highest thrust (0.06 N) and highest speed (0.106 m/s) compared to rectangle and triangle shapes. The nearest data recorded in this paper was for case B because only caudal fins acted as a propulsor where caudal fins were fixed in this experiment.

The rectangle shape gives the lower forward thrust (Case A and C) because the tip vortex for the rectangular shapes follows the trajectory of the tip edge without significant outward motion compared to the quarter-ellipse shape [9]. The robotic fish swims by transferring momentum to the water environment. The main factors that contribute to the momentum transfer to thrust and speed resistance are Re, frequency and shape [14]. Combes and Daniel [10] stated that the highest AR could generate more thrust but through the constant value of AR, a quarter-ellipse, triangle and rectangle shape of pectoral generated different thrust and indirectly contributed to the high speed. However, it is of note that the shapes of pectoral fins play a vital role in thrust and speed production.

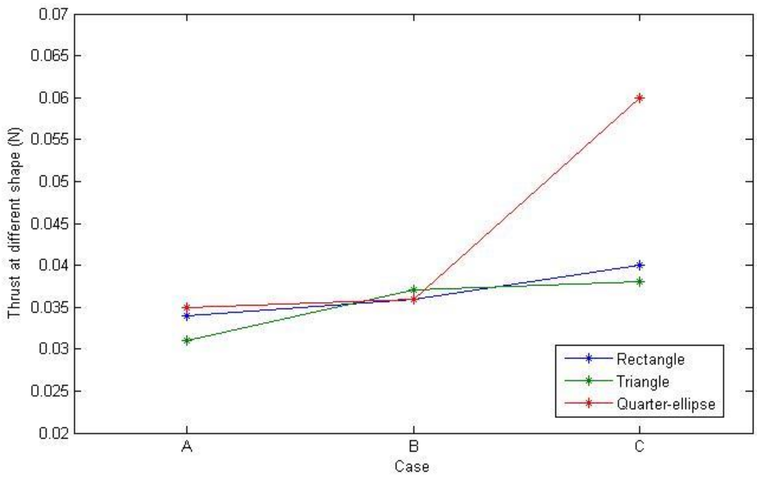


Fig. 10. Thrust produced by robot fish in case A, B and C.

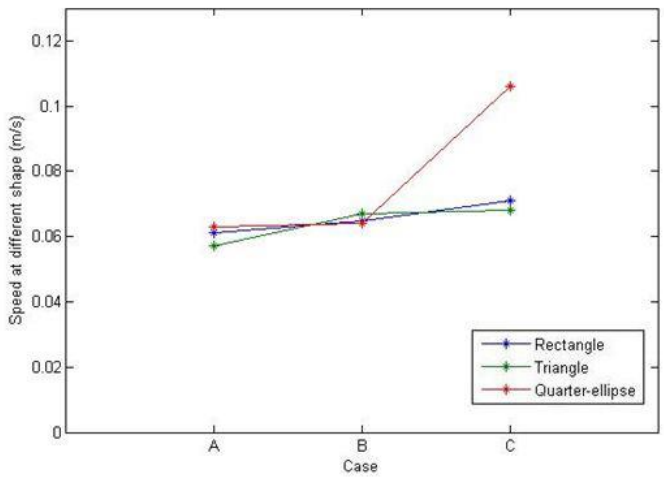


Fig. 11. Speed produced by robotic fish using different cases and pectoral fin.

3.2. Hydrodynamics

Water resistance is closely related to the Reynolds Number where it is classified by the type of flow regime, either laminar or turbulent. Figure 12 shows the results of Re Number for every case of robotic fish by using Eq. (6). The range of Re of the robotic fish is approximately 9405 to 17 655. This validates the range of Re for an adult fish swimming, which ranges from 1×10^3 to 5×10^6 [15]. At a lower Reynolds Number, a laminar flow is experienced by the robotic fins [15]. The values are greatly influenced by the characteristic length of body, velocity and kinematic viscosity of the aqueous environment. As the Reynolds number increases, the amount of inertial force also increases. In this case, Re value are in agreement with the velocity of the robotic fish with respect to the shapes (triangle, rectangle and quarter-ellipse).

Using Eqs. (7) and (8), the St and Fr number are generated and plotted as shown in Figs. 13 and 14. Lowest St Number for every case occurs at the highest forward speed of the robot fish. The St Number, which is a measure of thrust, decreased as the different shape of pectoral fins. The St Number of the fish robot as shown in Fig. 13 were 3.892 for the quarter-ellipse shape, 5.81 for triangle shape and between 6.066 for the rectangle shape of pectoral fin. For the fast swimmer fish, the St Number must be within the range $0.25 < St < 0.4$ [16]. However, for all the shapes are not in the range of St Number, there can conclude which the robot fish is not yet in the fast swimmer category [15, 16]. However, the St Number is overly simplified on many accounts. This is because velocity is poorly defined as the input fluid velocity across the pectoral fin can be significantly smaller than the output fluid velocity and velocity is neither constant nor evenly distributed across the fin [1, 17, 18]. Velocity is also wrongly assumed to be a single unidirectional vector when in actuality it is a spinning vortex [17]. As such, the Strouhal Number is an ineffective method of predicting pectoral fin performance for all but the most simplified scenarios

[17]. As a result, the findings open up the opportunity on the future work on correcting the relationship between pectoral shapes and St Number.

Another important parameter is a measurement of Fr Number. Fr number is a measurement of manoeuvrability and its represents the ratio of inertial force to gravity force in the flow [19]. Fr number tended to increases for the different shapes of pectoral fin and it reaches a maximum value 0.083 for the combination of quarter-ellipse pectoral fin with caudal fin. Due to the low Fr (< 1) for all shapes and cases, it can conclude that the inertial force of fish robot is less dominant than its gravity force, which means that it has very low manoeuvrability [16]. However because the combination of quarter-ellipse pectoral fins and caudal fin shows the highest Fr number, there is expected the quarter-ellipse propelled fish robot to show better manoeuvrability compare to the rectangle and triangle shape.

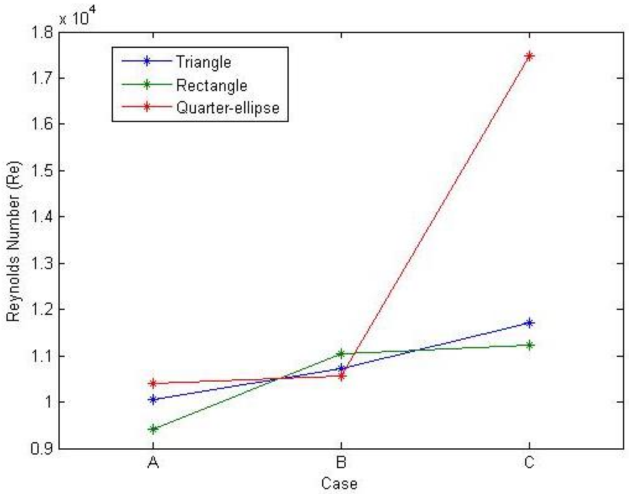


Fig. 12. Reynolds number at different shape of pectoral fin.

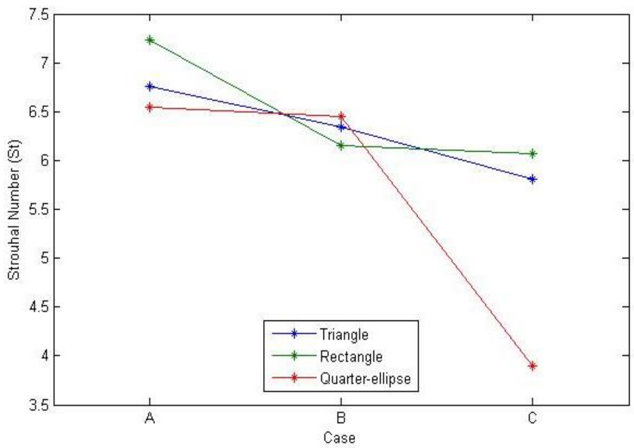


Fig. 13. Strouhal number at different shape of pectoral fin.

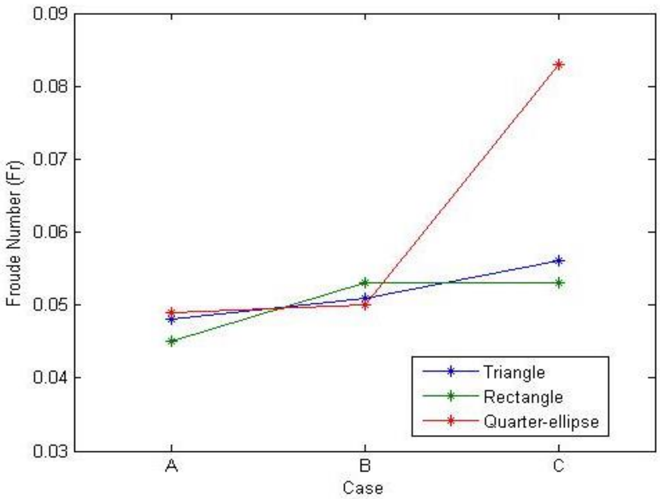


Fig. 14. Froude number at different shape of pectoral fin.

3.3. Steady turning diameter (STD)

Three types of pectoral fins have been tested to measure the values for STD with the same servo frequency. The results showed a quarter-ellipse shape gave the lowest radius of 37cm compared to the triangle which was 38.5cm, and the rectangle, which was 43cm. The manoeuvrability characteristics are very useful in a real situation in an underwater environment. The STD is independent of the rotational speed; a low speed is much preferred, especially in a confined and area of limited accessibility with a good performance in STD [8]. For manoeuvring, pectoral fins act as an important component, especially for low speed manoeuvring [6]. The angle of attack for fins gives a high impact to manoeuvring performance. All fins are controlled at certain angles to make sure that the stability is maintained while performing STD.

4. Conclusion

The comparisons of the three types of pectoral fins (triangle, rectangle and quarter-ellipse) were studied for thrust, speed and instead of as well as hydrodynamics. The quarter-ellipse shape give the highest thrust, 0.06 N (combination of pectoral and caudal fin), followed by triangle, 0.04 N, and rectangle, 0.038 N. The combination also give the combination of quarter-ellipse shape pectoral fin highest speed 0.106 m/s compared to triangle, 0.068 m/s and rectangle, 0.07 m/s Some concluding observations from the investigation are given below.

- The aspect ratio value for pectoral fins are constant but the thrust was generated is different. Quarter-ellipse generated higher thrust compares the triangle shape pectoral fin. Indirectly it is shows that shape of pectoral fins play a vital role in thrust and speed production of robot fish.

- The lower performance by rectangle was due to the tip vortex following the trajectory of the tip edge without significant outward motion compared to the other two shapes.
- Spanwise, flow also plays an important role in producing the thrust where the tip edge is wider; the tip vortex has the tendency to produce more forward thrust.
- A combination of the quarter-ellipse pectoral fin and the delta shape caudal fin gave the highest speed (m/s) to the fish robot with Re Number 1.749×10^4 and give the lowest St Number (3.892) for every case occurs at the highest forward speed of the robot fish. The maximum value of Fr number (0.083) propelled fish robot to show better manoeuvrability.\
- This combination also gave a good result in STD measurement, which was 37cm compared to others combinations.

References

1. Palmisano, J.S.; Ramamurti, R.; Lu K.J.; Cohen, J.; Sandberg, W.C; and Ratna, B. (2007). Design of a biomimetic controlled-curvature robotic pectoral fin. *IEEE International Conference on Robotics and Automation (ICRA)*, Rome, Italy.
2. Ghahferokhi, M.A.; and Abbaspour, M. (2013). Experimental hydrodynamics analysis of trout locomotion for simulation in robot-fish. *Journal of Basic and Applied Scientific Research*, 3(4), 221-226.
3. Yu, J.; Wang, L.; and Tan, M. (2005). A framework for biomimetic robot fish's design and its realization. *American Control Conference*.
4. Muller, U.K.; Stamhuis, E.J.; and Videler, J.J. (2000). Hydrodynamics of unsteady fish swimming and the effects of body size: Comparing the flow fields of fish larvae and adults. *Journal of Experimental Biology*, 203, 193-206.
5. Fukuoka, Y.; Kimura, H.; and Cohen, A.H. (2003). Adaptive dynamic walking of a quadruped robot on irregular terrain based on biological concepts. *The International Journal of Robotics Research*, 187-202.
6. Barbera, G. (2009). *Theoretical and experimental analysis of a control system for a vehicle biometric "Boxfish"*. Ph.D. Thesis. Universiti Studies in Padova.
7. Hoar, W.S; and Randall, D.J. (1978) *Fish Physiology*. New York: Academic Press Inc.
8. Lachat, D.; Crespi, A.; and Ijspeert, A.T. (2005). *BoxyBot the fish robot: Design and realization*. Semester Project Report Biologically Inspired Robotic Group (BIRG).
9. Kim, D.; and Gharib, M. (2011). Characteristics of vortex formation and thrust performance in drag-based paddling propulsion. *The Journal of Experimental Biology*, 214, 2283-2291.
10. Combes, S.A.; and Daniel, T.L. (2001). Shape, flapping and flexion: Wing and fin design for forward flight. *The Journal of Experimental Biology*, 204, 2073-2085.
11. Patar, E.S.; Yul, N.Y.; Edi, L.; and Agus, B. (2009). Design and implementation of paired pectoral fins locomotion of labriform fish applied to a fish robot. *Journal of Bionic Engineering*, 6, 37-45.

12. Spedding, R. (1992). *The aerodynamic of flight. In advances in comparative and environmental physiology*, Berlin: Springer-Verlag.
13. Park, Y.; Jeong, U.; Lee, J.; Kwon, S.R.; Kim, H.Y.; and Cho, K.J. (2012). Kinematic condition for maximizing the thrust of a robotic fish using a compliant caudal fin. *IEEE Transactions on Robotics*, 28.
14. Webb, P.W. (1998). Entrainment by river chub nocomismicropogon and smallmouth bass micropterusdolomieu on cylinders. *Journal of Experimental Biology*, 201, 2403-2412.
15. Sfakiotakis, M.; Lane, D.M.; and Davies, J.B.C. (1999). Revise of fish swimming modes for aquatic locomotion. *IEEE Journal of Oceanic Engineering*, 24, 237-252.
16. Seok, H.; Tedy, W.; Hoon, C.P.; and Nam S.G. (2007). Effect of an artificial caudal fin on the performance of a biomimetic fish robot propelled by piezoelectric actuators. *Journal of Bionic Engineering*, 4, 151-158.
17. John, S.P.; Ravi, R.; Jason, D.G.; Marius, P.; William, C.S.; and Banahalli, R. (2013). How to maximize pectoral fin efficiency by control of flapping frequency and amplitude. *Office of Naval Research*.
18. Ramamurti, R.; Sandberg, W.C.; Ohner, R.; Walker, J.; and Westneat, M. (2002). Fluid dynamics of flapping aquatic flight in the bird wrasse: Three-dimensional unsteady computations with fin deformation. *Journal of Experimental Biology*, 205, 2997-3008.
19. Bandyopadhyay, P.R. (2005). Trends in bio robotic autonomous undersea vehicles. *IEEE Journal of Oceanic Engineering*, 30, 109-139.