Design and optimization of Caudal fin for robotic fish driven by crank-slotted slider and lever mechanism

DOI : 10.36909/jer.ICMET.17187

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ABSTRACT

To explore the seabed as well as the depth, to perform the various tasks in an underwater environment, to study the behavior of aquatic animals many researchers and scientists have developed underwater autonomous vehicles using different techniques. After going through all the robotic fishes developed in the last decade, we have developed a novel way and technique to enhance the speed of the robotic fishes under a certain range (30-40cm) of robotic body length. A crank-slotted slider and lever mechanism-based mechanism and fin have been designed to produce a forward thrust up to 25gmf. In the above system, the rotational motion produced by the DC motor is translated to oscillatory motion using a crank-slotted slider mechanism. The mechanical advantage is enhanced by the use of a certain length of the lever. Finally, for the given system a mathematical fin formula is introduced, tested, and implemented.

Keyword: Robotic fish, Caudal fin, Underwater Vehicle, crank-slotted slider, forward mechanism.

INTRODUCTION

About two-third of regions of the earth is enwrapped with the waterbed. Plenty of natural resources are hidden under the depth of the sea. Various types of sea animals and related behaviour are yet to be explored. Besides the depth of the sea, the surface of the ocean is also the biggest resource of energy like solar and waves. Nowadays, different types of agriculture technologies have been introduced for growing food over the surface of the ocean which can fulfil the food requirements of the largest population of the world, which never happened before. For performing different tasks on the surface as well as the depth of the ocean different underwater autonomous vehicles (UAVs) have been developed. Most of the UAVs are inspired by the fish due to their simple body design, higher forward velocity, enriched with various motion dexterity and manoeuvrability.

To date, a number of technologies have been introduced in the advancement of robotic fishes. Servomotor based technologies have been used mostly for developing robotic fish. Studies show Among Approx. more than 70% conventional actuators, more than 50% servo motor type actuators have been used in the last decade for actuating robotic fishes. Some of the recently developed robotic fishes are briefly discussed below. A servo motor based robotic fishes (Zuo et al. 2020) have been developed and designed by. Servomotor was used to oscillate the caudal fin which enable the robot to move forward. Electrolyser gas generator based buoyancy control mechanisms has been introduced. A robotic fish having been developed having body size was about 29cm and it achieved a speed of 17.6cm/s. servomotor was not used directly to oscillate the caudal fin (Zheng et al. 2020). A link mechanism was used to boost the thrust applied by the caudal fin. Up and dive motion was achieved by varying the centre of mass along the body length of the robotic fish using a Lead screw mechanism. Flexible folding pectoral fins driven robotic fish, actuated by servomotor was developed (Pham et al. 2019). A multi-joint robotic fish was developed (Chen, Wu, and Yu 2019). The one third body part of the robotic fish consists of three servo motors and two servo motors were used to actuate pectoral fins. The caudal fin was actuated using a passive joint.

DC motor is also used by different researchers to develop robotic fish. In these types of robots, various link mechanisms for converting rotational motion to linear are used. A high-frequency DC motor based robotic fish was designed and developed (Zhu et al. 2019). A crank attached with a high-speed motor and slider slotted mechanism was used to actuate the robotic fish. A DC motor actuated robotic fish was designed (Lu et al. 2019). Two third of the posterior body part was worked based on the passive flexible mechanism.

In this article, a novel technique for designing and developing the highest forward thrust using a DC motor actuated crank-slotted slider and lever mechanism has been introduced. Our target is to develop forward thrust, so that a maximum forward speed greater or equal to 1.2m/s can be achieved. Different experiments have been performed on six fins made of two types of materials in support of the developed mathematical model. Their shape and size have been chosen based on the related mathematical calculations.

FORWARD SWIMMING MECHANISM DESIGN

DC motor based crank-slotted slider and lever mechanism have been designed, tested and applied as shown in (Figure 1). This mechanism translates rotational motion to oscillatory motion in minimum possible space (Costa et al. 2018). It is moreover similar to the mechanism used in hair cutting trimmer. The above mechanism consists of four links, four lower pair kinematic pairs (Mehregany, Gabriel, and Trimmer 1997) (among them three revolute joints and one prismatic joint) and one cam-follower types' higher kinematic pair. The crank connected with a DC motor via revolute joint and connected to the slotted slider link via cam-follower type joint. Again the slider connected to the body structure via prismatic joint and connected to the lever via revolute or pin joint. Finally, the lever modifies the oscillatory motion with help of the revolute joint also called a fulcrum.

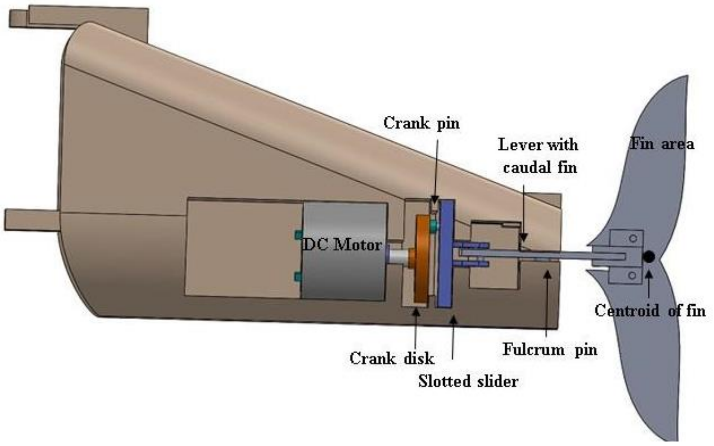


Figure 1. CAD Model of caudal fin along with oscillatory system.

The caudal fin is attached to the other end of the oscillating link or lever. When the oscillation of the caudal fin takes place, forward thrust generates on underwater robotic vehicles. This thrust causes a forward motion against the different resistive forces like- inertia force due to the robotic body in rest, drag force and resistive force generated due to body skin friction. For rotating crank (Tey and Sidik 2015) disc a DC motor has been used as shown in figure 2. The eccentrically connected link causes the oscillation of the slotted slider along the guide made on the frame. Now using a simple lever mechanism this oscillatory input power is transmitted to the caudal fin via a simple lever mechanism as output. A high-speed DC motor has been selected and based on the dimension of the DC motor the crank disk has been designed. Based on robotic body size, the length of the lever and based on the study, (Matta et al. 2019) the rowing angle or swipe angle for the caudal fin has been decided for developing a thunniform type swimming. The dimensions of the mechanism have been shown in figure 2.

Mathematical modelling

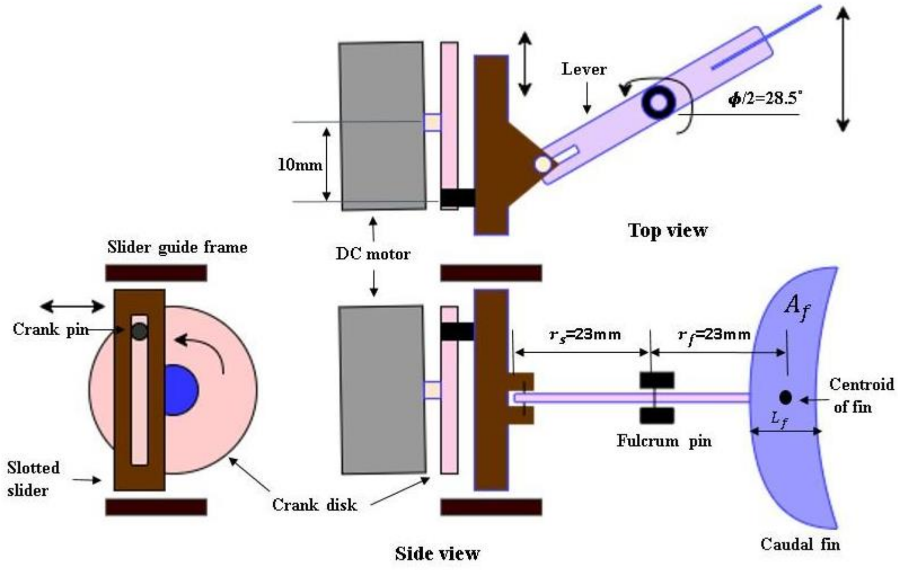


Figure 2. Schematic diagram of crank-slotted slider and lever mechanism for oscillating caudal fin.

In case of simple lever mechanism,

Power input at crank pin side of the link = Power output at the fin side of the link

Or, $T_c\omega_c = T_f\omega_f$

Or, $F_c r_s \omega_c = F_f r_f \omega_f$

Mechanical Advantage (MA) of link= $= \frac{F_f(Output\ force\ at\ fin)}{F_c(Input\ force\ at\ crank\ pin)} = \frac{r_s\omega_c}{r_f\ \omega_f} = \frac{r_s}{r_f}$ as $(\omega_c = \omega_f)$

Eq. 1

So, force at fin (F_f) is directly proportional to the input side link length (r_s) of the lever connected with crank pin. But the value of r_c can't be increased above certain value for a given model because the angle travel by fin or angular stroke (swipe angle) travelled by the caudal fin reduces. Considering for MA=1, all the forces developed at the crank pin is transmitted to caudal fin. We have,

$$r_s = r_f$$

So, for developing mechanical advantage equal to one, the shape of the fin is designed so that the centre of area of the caudal fin concentrated and coincide with the end point of the output fin side link.

Forward thrust force (F_t) generated by caudal fin,

$F_t = forward\ component\ of\ drag\ force(F_d) +$

$reaction\ force\ due\ to\ mass\ of\ water\ thrown\ back\ by\ the\ caudal\ fin(F_r)$

From the newton’s third law of motion,

$$Reaction\ force\ due\ to\ mass\ of\ water\ thrown\ by\ the\ caudal\ fin\ (F_r) = m_f\ .\ a_{th}$$

Where, m_f = mass of water thrown backward by the caudal fin and a_{th} = horizontal component of tangential acceleration of the caudal fin along the body length of robotic fish.

Mass of the volume swept along the area ‘abcd’ (figure 3) for the given system will be,

$$m_f = 211.1 A_f\ L_f \qquad \text{Eq. 2}$$

Where, A_f = area of caudal fin, L_f = horizontal Length of fin

And horizontal component of tangential acceleration equal to:

$$a_{th} = \int \frac{2\, r_f \phi}{{t_s}^2} sin(\phi/2)\ d\phi \qquad \text{Eq.3}$$

And drag force developed by the caudal fin is given by,

$$drag\ force(F_d) = \int \frac{1}{2}\, C_d\, \rho\, A_f {V_{tf}}^2\ sin\ sin\left(\frac{\phi}{2}\right) d\phi$$

Eq.4

So, the forward thrust developed by one half of the stroke or swipe angle of the caudal fin is given by

$$F_{th} = (\frac{1}{2}\, C_d\, \rho\, (\frac{2\, r_f \phi}{t_s})^2 + 211.1\, L_f\, \frac{2\, r_f \phi}{{t_s}^2})\, A_f \left(\frac{\phi}{2}\right) d\phi \qquad \text{Eq.5}$$

And the total forward thrust $(F_t) = 2\, F_{th}$ Eq.6

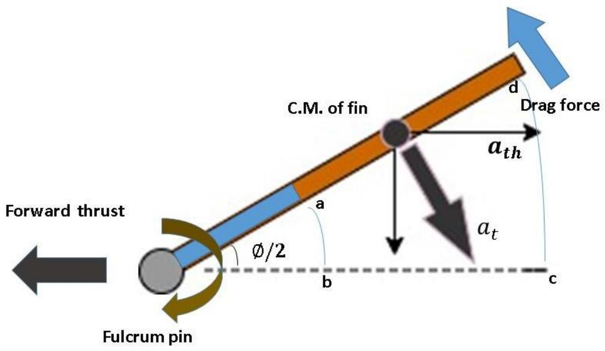


Figure 3. Schematic diagram showing different forces on robotic caudal fin.

Finally, by solving the above expression assuming average tangential force applied by fin exerted about the centre of area of the fin with a constant angular velocity, we have

$$F_t = 2A_f(\frac{1}{2}\, C_d\, \rho\, (\frac{2\, r_f \phi}{t_s})^2 + \quad 211.1\, L_f \quad \frac{2\, r_f \phi}{{t_s}^2}) \quad sin\, sin \left(\frac{\phi}{2}\right)$$

Eq.7

Choice of fin

It is found that for a certain range of robotic body length (30-40cm) and types of actuators (DC motor) used, 1.04m/s was the maximum velocity achieved till date. We have decided to develop another underwater autonomous vehicle whose body specification have been mentioned in the table.1 below.

Table 1: Showing the characteristic properties of robotic fish.

Sl. No.	**Characteristic properties**	**Values**
1.	Target forward speed require	1.2m/s
2.	Calculated forward thrust require	20gmf

3.	Robotic body length	39cm
4.	Cross sectional area	7040 mm^2
5.	Body weight	1.6 kg
6.	Drag coefficient	0.04 (considering stream line body design)
7.	Material used	Polly Lactic Acid (PLA)

We have critically reviewed all the robotic fishes actuated using DC motor in which rotational motion is converted to oscillatory motion using a four-bar mechanism. A crank-slotted slider and lever mechanism have been chosen for producing oscillatory motion due to the presence of less link and operating space. Figures 4 & 5 are showing different fin profiles. Among all, such fin profiles have been chosen having maximum area (A_f) for minimum horizontal width (r_f) with minimum drag coefficient. So that centre of mass of the swept water volume to be thrown back concentrate at the end of the lever and fin travel relatively faster. Finally, fin-a (figure 5) having a mixed fin pattern between the Forked and Lunated (figure 4) has been taken into the consideration for further experimental tests.

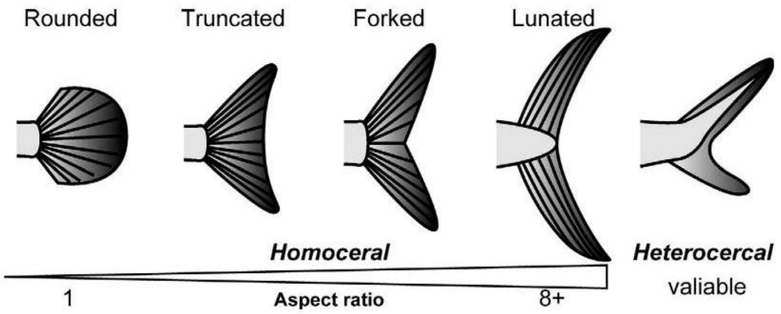


Figure 4. Nomenclature of different types of caudal fins (Kikuchi 2018).

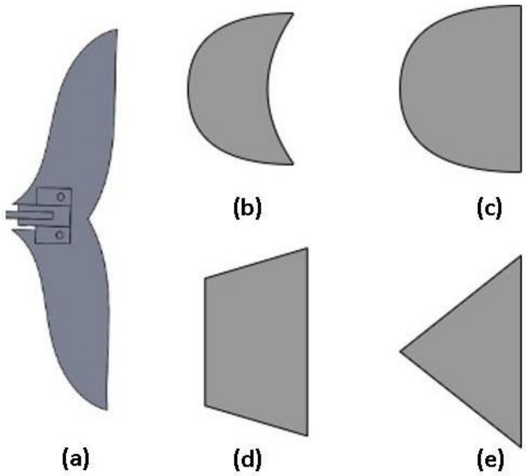


Figure 5. Various fin profile that can be used for developing caudal fin.

Two types of material have been used for developing six fins (figure 6). The specification of materials and the fins have been shown in Table 2 and Table 3. The predicted area and the width of the fins are found by the reverse calculation using mathematical formula given (Eq.7) to generate about 20gmf forward thrust.

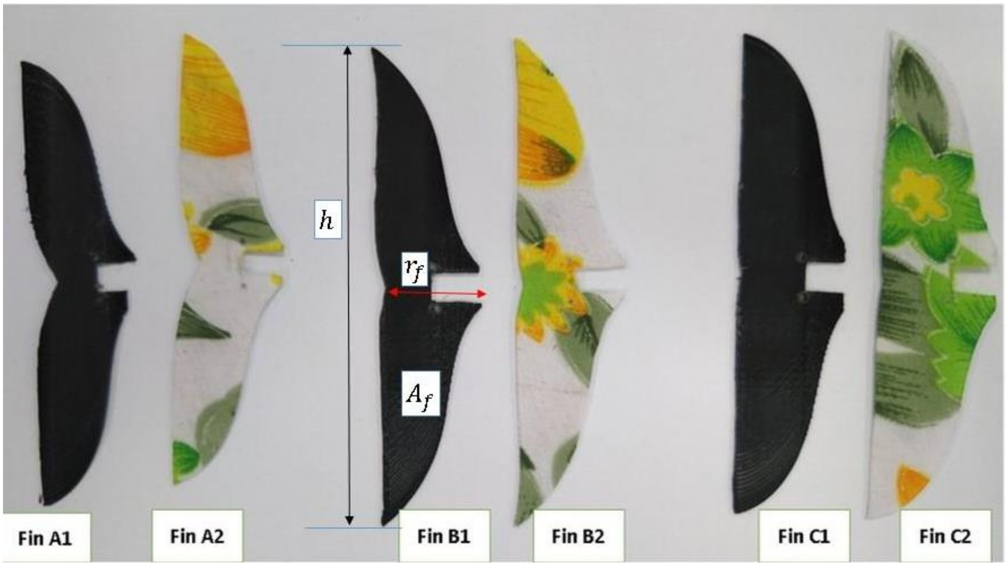


Figure 6. Different fin developed at our lab for testing.

Table 2. Specification of material used for making fins.

Sl. No.	Material	Specific Gravity	Flexural modulus(MPa)	Melting point (°C)

1.	Poly lactic acid (PLA)	1.24	3840 (avg.)	150-160
2.	Polypropylene(PP)	0.9	1575 (avg.)	160-163

Table 3. Specification of fins.

Sl. No.	Types of Fins	Area of fin profile (A_f) (mm^2)	Dimension of fin (mm) ($h \times r_f \times t$)	Weight of fin (g)
1.	Fin A1 (PLA)	1800	($110.5 \times 30 \times 1$)	2.23
2.	Fin A2 (PP)	1800	($110.5 \times 30 \times 1$)	1.62
3.	Fin B1 (PLA)	2000	($120.5 \times 35 \times 1$)	2.48
4.	Fin B2 (PP)	2000	($120.5 \times 35 \times 1$)	1.8
5.	Fin C1 (PLA)	2500	($118.7 \times 40 \times 1$)	3.1
6.	Fin C2 (PP)	2500	($118.7 \times 40 \times 1$)	2.25

Experimental setup

Figure 7 shows the experimental setup. The whole mechanism is fully submersed into water kept in the tub. One third body part of the robotic fish has been printed using Polylactic Acid (PLA) and required parts (DC motor, crank, slider, lever, and caudal fin) and related systems are fitted into it.

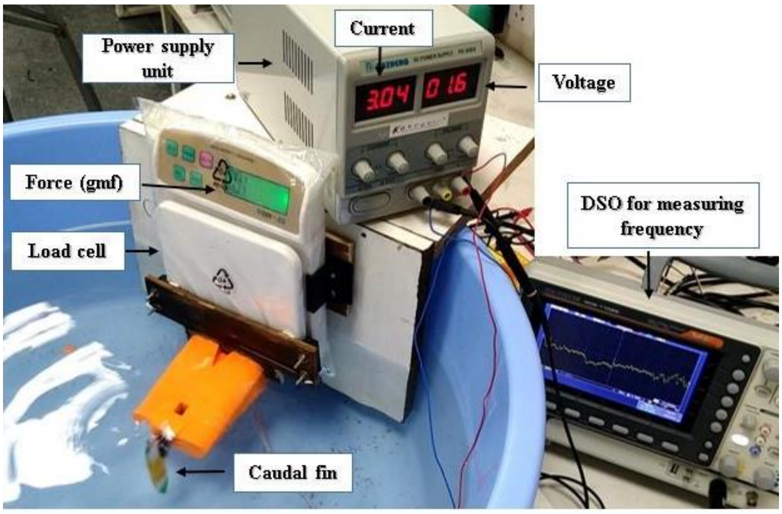


Figure 7. Experimental Setup.

The output end of the lever is designed so that different fins can be mounted easily. The body structure of the robotic fish has been mounted over a digital weight measuring device containing a load cell. The power supply unit has been used to supply power as well as to measure current and voltage. Digital storage oscilloscope (DSO) has been used for measuring frequency based on voltage fluctuation that occurred during the operating stroke of the caudal fin.

RESULTS AND DISCUSSION

Figure 8 shows a graphical relation between theoretical values of forwarding thrust with rotation of crank per second for different fins. The curve obtained is a half parabolic function and forward thrust increase quadratically with fin frequency. The graph clearly shows for a given fin frequency the calculated forward thrust is greater for the fins having higher fin area. At the same time, it also shows, for producing a given amount of forwarding thrust the fin having a higher fin area, would have lesser fin frequency.

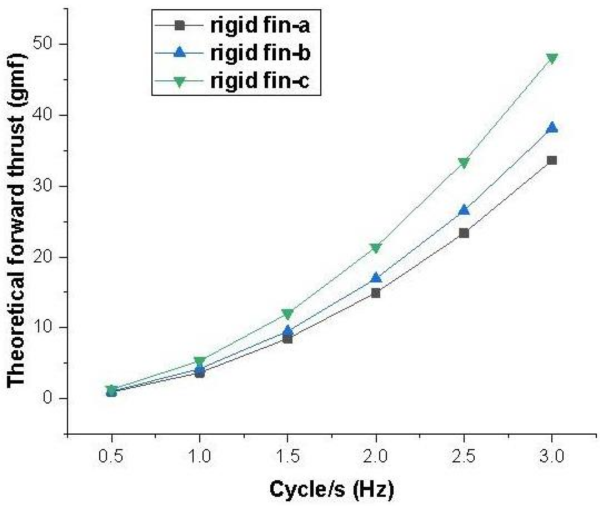
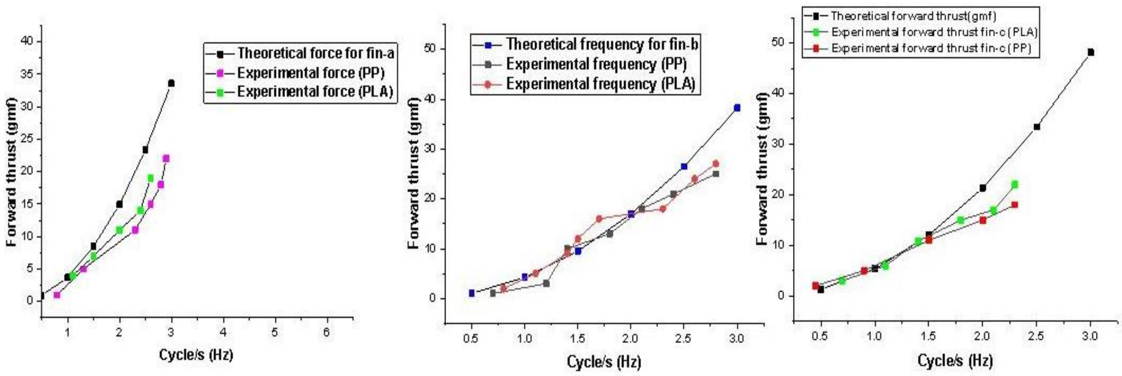


Figure 8. Theoretical value of forward thrust with respect to rotation of crank per second.

Figure 9 shows the graphical comparison between the theoretical and experimental values for fin a, fin b and fin b respectively. PLA material based fin gives more satisfactory results than the others up to a certain range of fin frequency. Below a certain frequency range, all fins are matching with the theoretical values but above that, the experimental values divert due to various reasons like types of material used for making fin, size and shape of the fins. Fin-a (PLA) almost matches the theoretical values up to the 1.5Hz frequency range. Fin-b (PLA) almost matches the theoretical values up to the 2.5Hz frequency range. Whereas Fin-c (PLA) almost matches the theoretical values up to 1.75Hz frequency range. Figures 10 & 11 are showing the variation of forwarding thrust (gmf) developed by different fins with input power (J/s). Up to 40J/s input power, all fins develop about 18gmf forward thrust. Fin-b (PP) develop a forward thrust of about 25gmf from the input power of about 60J/s. for the smallest fin-a, the forward thrust increase rapidly up to 30J/s input power but above that the forward thrust increase slowly even we increase the input power. For fin-b, both material types of fins work equally.



(a) **(b)** **(c)**

Figure 9. Comparison of fin for theoretical and experimental values (a) fin-a (b) fin-b (c) fin-c.

The forward thrust developed by the fin-b increased rapidly up to 65J/s input power. In the case of the biggest fin-c (PLA), the forward thrust increase rapidly above 70J/s input power but for fin-c (PP) the forward thrust increase rapidly up to 35J/s input power due to higher flexibility and less capability to through the water back. Figure 12 shows the values of Mechanical Advantages (MA) obtained with respect to various fins (Eq.1). The figure clearly depicted how the MA reduces with an increase of fin size due to the outward shift of the centre of mass of the caudal fin.

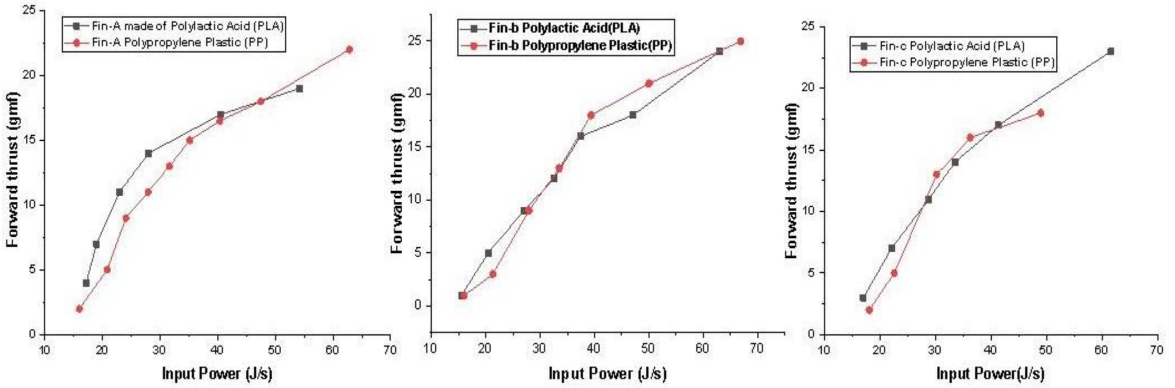


Figure 10. Variation of forward thrust with input power for fins made of PLA and PP. fin-a (left), fin-b, fin-c (right).

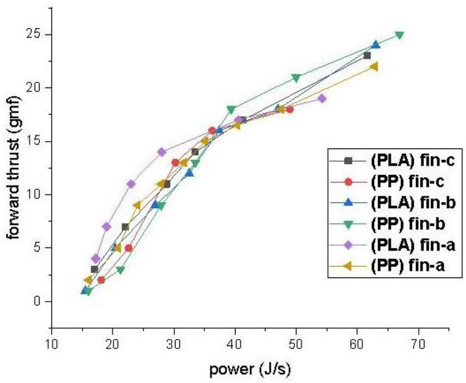


Figure 11. Variation of Theoretical values of forward thrust with fin frequency for fin-a, fin-b, and fin-c.

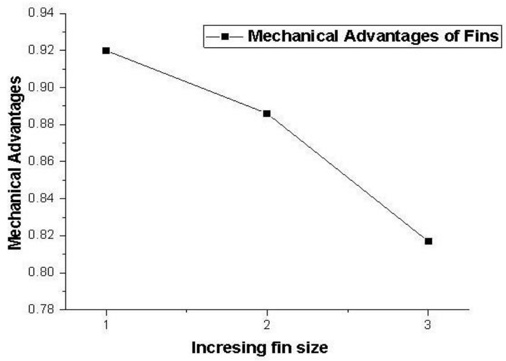


Figure 12. Mechanical advantages of fin attached with fin.

CONCLUSIONS

- By increasing the fin area, fin length, the maximum angle travelled by fin (ϕ), the value of drag coefficient (C_d) of fin, the density of the fluid (ρ), and reducing the square of the time to travel one angular stroke by fin, the forward thrust can be increased.
- Up to a certain fin frequency, all fins match the calculated value but above that value, the observed value starts diverting from the calculated results proportional to their flexibility.
- The fin material having less flexural modulus (PP) divert more.
- Up to 1.5Hz frequency fin-a made of PLA develop highest forward thrust among all for up to 35J/s power input.
- Up to 2Hz frequency fin-b made of PP develop highest forward thrust among all for up to 55J/s power input.
- Mechanical Advantages of a lever attached with different fins, reduce with increase of fin size.
- Throughout the observations fin-b made of PLA, moreover matches the calculated values and is accepted for the further development of robotic fish.

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