DEVELOPMENT OF A MECHANICAL FISH PROTOTYPE WITH VARIOUS TAIL PLATFORMS

by

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ENDORSEMENT

I, Sharviin Raaj A/L P.Muniandy hereby declare that I have checked and revised the whole draft of dissertation as required by my supervisor.

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DECLARATION

This thesis is the result of my own investigation, except where otherwise stated and has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any other degree.

(Signature of Student)

Date: 11/07/2021

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DEVELOPMENT OF MECHANICAL FISH WITH VARIOUS TAIL PLATFORMS

ABSTRACT

The study of biomimetic robot has been popular among researchers in recent decade. This thesis describes the research done on mechanical fish with various tail platforms. The mechanical fish prototype is designed using SOLIDWORKS 2019 and is specified with PLA material. The mechanical fish designed consists of 8 integrated parts that fits each other consisting of 57 faces throughout the model. Type of tail for the mechanical fish is chosen to be truncate type of tail which was designed with 3 sizes to validate the purpose of the study. The sizes used for the truncate tail is 11cm ,8cm, and 5cm. Since the experiment is deduced as half simulation and half experimental. The mechanical fish prototype is printed using Anycube Mega S 3D printer. Two servos are fitted in the mid body section and back end of the mechanical fish. An Arduino board is used to program the angle of deflection of the body and tail end of the prototype to the servos and a 9V battery is used as a power source. Three tail platform with various size is 3D printed as mold and silicon is poured into them to create three silicon tails with different sizes with a range of tail length of 5cm, 8cm and 11 cm. The main objective of this research is to measure the drag performance of the mechanical fish. The analysis of the prototype is performed using ANSYS 2021. The servos are programmed to deflect at an angle of 15,20 and 25 degree at mid body and tail end respectively. The same type of movement is programmed in ANSYS 2021 with different type of tail to compute the data of total drag that is acting upon the fish when it is projected with water speed of 0.28 m/s which mimics the speed of Gourami fish. The data result is showed and justified and the best model with less drag is chosen to be printed as a mechanical fish model. Thus, this experiment is essential to the study of mechanical fish using 3 joint mechanisms as less research material is available for it.

PEMBANGUNAN IKAN MEKANIKAL DENGAN PELBAGAI JENIS EKOR

ABSTRAK

Kajian robot biomimetik telah popular di kalangan penyelidik dalam beberapa dekad kebelakangan ini. Tesis ini menerangkan penyelidikan yang dilakukan terhadap ikan mekanikal dengan pelbagai platform ekor. Prototaip ikan mekanik direka menggunakan SOLIDWORKS 2019 dan ditentukan dengan bahan PLA. Ikan mekanikal yang dirancang terdiri daripada 8 bahagian bersepadu yang saling sesuai yang terdiri daripada 57 muka sepanjang model. Jenis ekor ikan mekanik dipilih menjadi ekor terpotong yang dirancang dengan 3 ukuran untuk mengesahkan tujuan kajian. Ukuran yang digunakan untuk ekor terpotong adalah 11cm, 8cm, dan 5cm. Oleh kerana eksperimen ini disimpulkan sebagai separuh simulasi dan separuh experimen. Prototaip ikan mekanikal dicetak menggunakan pencetak 3D Anycube Mega S. Dua servoi dipasang di bahagian tengah badan dan hujung belakang ikan mekanikal. Papan Arduino digunakan untuk memprogram sudut pesongan badan dan hujung ekor prototaip ke servoi dan bateri 9V digunakan sebagai sumber kuasa. Tiga ekor dengan pelbagai ukuran dicetak 3D sebagai acuan dan silikon dituangkan ke dalamnya untuk membuat tiga ekor silikon dengan ukuran yang berbeza dengan jarak panjang ekor 5cm, 8cm dan 11 cm. Jenis ekor yang digunakan dibuat pemalar iaitu ekor terpotong. Objektif utama penyelidikan ini adalah untuk mengukur prestasi ikan mekanikal dari segi seretan yang disebabkan oleh ikan mekanikal. Analisis prototaip disimpulkan menggunakan perisian CFD seperti ANSYS 2021. Servos diprogramkan untuk memesong pada sudut 15,20 dan 25 darjah pada pertengahan badan dan hujung ekor masing-masing. Jenis gerakan yang sama diprogramkan di ANSYS 2021 dengan jenis ekor yang berlainan untuk menghitung data seretan total yang dilakukan pada ikan ketika diprojeksikan dengan kelajuan air 0.28 m / s yang meniru kepantasan ikan Gourami. Data yang diperoleh dari

perisian dibenarkan dan model terbaik dengan seretan yang sedikit dipilih. Oleh itu, kajian ini sangat penting untuk modal ikan mekanik yang menggunakan 3 sendi kerana kajian terhadapnya adalah terhad.

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CHAPTER 1

INTRODUCTION

1.1 General overview

Without a doubt robot have changed the human history in a big scale as they help humans in many ways such as lifting heavy objects, exploration of space and the list could go on and on. The robotic field is growing at an exponential rate in every country due to their advantages that the field can provide. Furthermore, there is a robotic field that is known as biomimetics which mimics a biological creature. The mimicking process may include its shape, movement aerodynamics or anything from nature because as we know it mother nature is the best engineer. There are also robots that are inspired by animals around us such as birds, lizards, insects, and fishes. The fields that will be the focus of this study are studies under biomimetics is mechanical or robotic fish. Mechanical fish is a vast field of study, and it is very popular among scientists due to its benefits. Thus this research is an valuable asset to the society.

What are robotic fish? They are defined as an aquatic vehicle that is shaped like a fish which moves itself through movement of its body or fin or both combined. Research on mechanical or robotic fish has been around for more than half a century which dates to 1960's. However, the fist robotic fish was developed in 1994 named Robo Tuna in Massachusetts Institution of Technology using gears, stainless steels, and cables from wire (MIT's Robotic Fish Takes First Swim, MIT News. Massachusetts Institute of Technology, 2020.). The biomimetics movement of the fish like vehicle is more favored than the propeller driven aquatic vehicles as it has its advantages over propeller. It is possible to reach great speeds and agility in bioinspired robotic fish than propeller driven aquatic vehicle with much less and much more long-lasting power.

1.2 Problem statement

Robotic propulsion falls under two category which is body and caudal fins (BCF) or median and paired fin (MPF) propulsion. (Videler, 2001). In this project, a mechanical fish consisting of three joint flapping mechanism is designed from inspiration from Carangiform locomotion. Carangiform is chosen out of all locomotion of fish such as Thunniform, Subcarangiform, Labriform, Tetraodontiform and Ostraciiform is because of its vast number of fish species falling under Carangiform as its locomotion, details of locomotion of fish will be described in chapter two. The biomimetic fish robot should propel itself in a straight horizontal path to make full use of it. The development of mechanical fish can benefit the society in many ways thus the problem statements of the study include:

1. Detecting water pipe leaks underwater.
2. Underwater exploration and fish behaviour monitoring without disturbing the habitat of fish.1
3. Underwater Mine counter measures use in application military field.

1.3 Research Objective

The purpose of this final year project is to evaluate the drag performance for 3 different mechanical fish tails. The projects involve the development of mechanical fish which involves designing, fabricating, and simulation a mechanical fish with different tail configuration. Thus, the objective of this work is to:

1. Development of a robotic mechanical fish
2. Evaluate the drag performance produced by different tail sizes and at different angle of tail deflection using numerical solution.

1.4 Research Benefits

It has been proven on many occasions that building a robotic fish can be beneficial with simplicity, high efficiency, waterproof and stable as it can help us in many ways. There are many uses of mechanical fish in various field such as studying and understanding the locomotion of fish (Brücker & Bleckmann, 2010). In his book he has concluded that a pair of two vortex ring is being shed instead of one vortex ring which is formed by the undulatory body movement and tail movement. This shows us that mechanical fish can be used to further understand the behavior and locomotion of fish without using a live specimen.

Besides that, it has been proven that mechanical fish can be used in a reconnaissance mission (How "Mantabot" Robot Fish Could Help Navy Missions, Live Science, n.d.). Based on the article it states that U.S. Navy funded University of Virginia in this project to research and build 'Mantabot' which was inspired by cow-nosed ray a close relative to manta ray and stingrays. This robotic ray could hold position and move fast in an instant which will be an important feature for underwater drone in the future. Its naturally inspired shape will not disturb ocean creatures as a bonus.

Furthermore, mechanical fish could be used to detect pollution in the water. This was tested and validated by researchers from Chonnam National University in South Korea. (Shin et al., 2007). The mechanical fish that the researchers build had GPS and obstacle avoidance sensors build in it which enabled the mechanical fish to move without any supervision of human. The mechanical fish was also having a few sensors to detect the pollution such as Vernier LabPro sensor, Dissolve oxygen sensors, pH sensors and Oxidation Reduction potential sensors which help to measure water pollution level.

1.5 Thesis Outline

Second chapter is the literature review that has been performed for this study. It consists of basic study of type of fins present in a fish such as dorsal fin, pelvic fin, pectoral fin, anal fin, and caudal fin. Chapter 2 also helps us fully understand the locomotion involved through the fish species. Thus, helping us to understand the movement of fish and aiding us in deducing the design the mechanical fish. The subsections also include case finding of mechanical fish that was developed by many researchers throughout the world which gives the overall picture where the development of mechanical fish stands.

Third chapter consist of metrology which specify how work is done throughout the study. This chapter specifies the designing process using SOLIDWORKS 2019 Premium SP4.0 and the complete setup of ANSYS 2021 Student Version is used to compute the data of the mechanical fish model. It also includes the reasons for why each step is done to reduce the errors in data compilated.

Fourth chapter in this thesis paper shows the results obtained from the mechanical fish simulation in ANSYS 2021. This chapter also consists of the analysis, discussion and justification of the data computed in the simulation together with the flow simulation comparison of the mechanical fish having highest and lowest drag. The flow simulation data will enable us to discuss the vortex formed on the mechanical fish model.

The final chapter in this thesis is chapter five which is composed of conclusion and recommendation for future works. This chapter also explains in detail of the limitation and the findings from this study.

CHAPTER 2.0

LITERATURE REVIEW

2.1 Theory

Fish as we know it are very fascinating creatures that dwell the waters in the seas or in the river. They are subdivided into 2 categories known as, saltwater fish and freshwater fish. They can smell, sense, feed, reproduce and move using their body motion and fins. Each species of fish has evolved to have specific sets of fins to help them swim efficiently according to their geological location and it reflects in its lifestyle. These fins play an important role in the fish's efficiency in swimming performance. The type and functions of the fins are listed and described as below referred from (Fish Fins: Types, Modification and Functions, Biology EduCare,2020.)

2.1.1 Dorsal fins

Dorsal fins are placed in the back or the top of the fish's body. This particular fin prevents the fish against rolling and helps the fish with turns and stops. Proximal, central, and distal dorsal fins are the main 3 categories. There are many types of dorsal fins which is listed in the below (Fish Fins: Types, Modification and Functions, Biology EduCare, 2020.). The importance of the dorsal fins are to prevent the fishes from rolling which will help it to yawing and stop.

I. Single
II. Split
III. Pointed
IV. Triggered
V. Spine triangular

2.1.2 Pelvic fins

These fins are located below and behind the pectoral fins and they are in pairs. In some species of fish, the pelvic fins are situated in front of the pectoral fins (Fish Fins: Types, Modification and Functions | Biology EduCare, 2020.) . Fishes that have pelvic fins are categorized as teleost apart from paddlefishes, freshwater garfish, sturgeon and bow fish. There is a big range for teleost as they consist 49% of all vertebrates and are separated into 4278 genus and 488 families (Nelson, 2006) This fin helps the fish to move upwards or downwards in its natural habitat which is crucial for the survival of the fishes. In manta and skates the pelvic fins are used to propel the fish forward by pushing off water. There are many species of teleost, and they are categorized in the Figure 2. 1 based on (Yamanoue et al., 2010). Thus this fin also helps the airbreathing fishes to move up to the surface to get air.

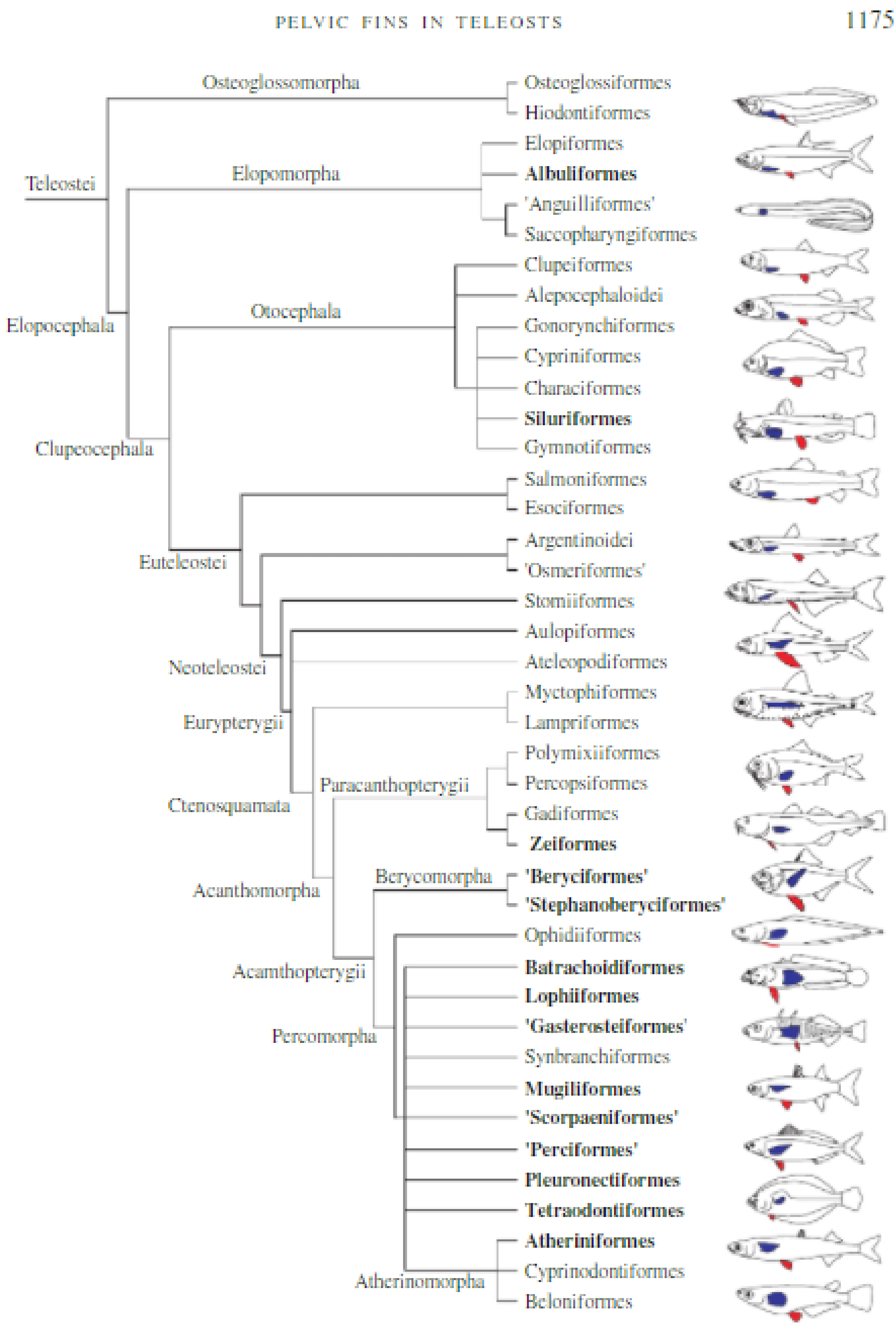

Figure 2.1: The relationship between teleost according to the molecular phylogenetic analysis. (Yamanoue et al., 2010)

2.1.3 Pectoral fin

Pectoral fins are the fins that are located at both sides of the fish. The function of this fin is to produce lift force and control movement (Fish Fins: Types, Modification and Functions, Biology EduCare, 2020.) of the fish, right and left. They also help the fish to maintain depth. These fins shape are essential in undertsanding the thrust mechanics of the swimming mode and manuverability of the fishes. Fins that are more rounded, broaded distally and paddle shaped fins are capable of producing stronger thrust for manuverebility while fins that are slendered, tapered and wing like fins is essential for fishes to sustain high speed using stroking of fins. (Westneat et al., 2004). The type of locomotion of these fishes are determined by the fin's aspect ratio (AR), its chord length and ditribution of pectoral fins. Figure 2. 2 shows the pectoral fins of the boxer fish. Thus, pectoral fins that has higher AR are commanly narrow and has a longer leading edge.

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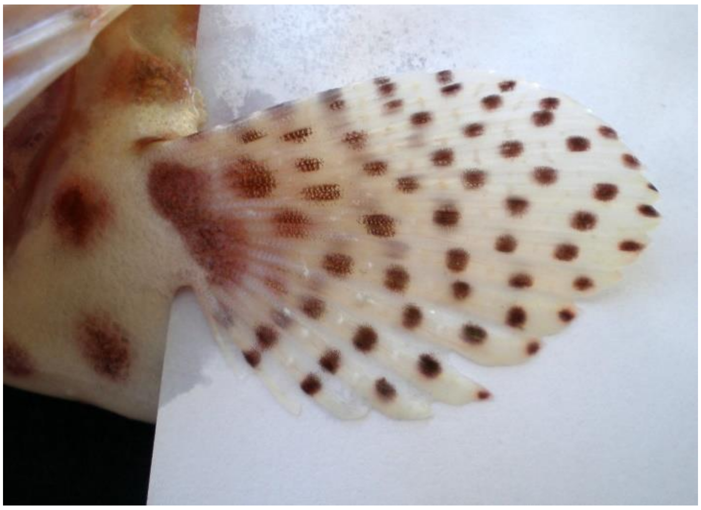


Figure 2.2: Pectoral fin of boxer fish

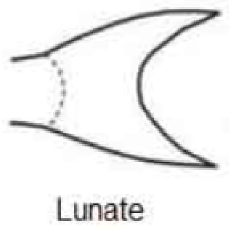
2.1.4 Anal fin

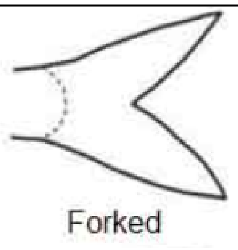
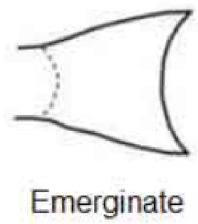
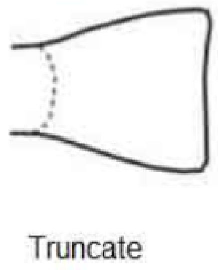
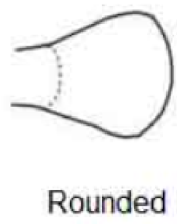
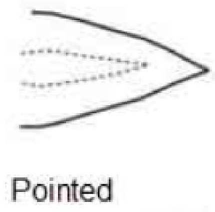
Anal fins are located just behind the anus of the fish, and it is also known as cloacal fin. The function of this fin is to control the rolling motion of the fish when it swims and to support the dorsal fin. Anal fins can also function as a sex organ in some species such as in Ayu *Plecoglossus altivelis.*(Iguchi et al., 1991). In a nutshell, anal fins are important in rolling and thrust motion of fishes.

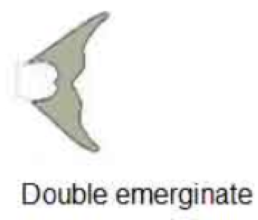
2.1.5 Caudal fin

Caudal fin is also known as tail of the fish as the function of this fin is for the locomotion of the fish. This fin is normally located in the rear end of the fish's body. The shape of this fin may vary between different species of fish as they adapt according to their surroundings. The types of caudal fins are listed in Table 2.1 and modified from ((Fish Fins: Types, Modification and Functions, Biology EduCare, n.d.). In short, caudal fins are the main source of thrust for most fishes.

Table 2.1: Types of caudal fins (Fish Fins: Types, Modification and Functions, Biology EduCare, n.d.)

Type	**Description**	**Example**
Lunate or crescentic	Found in fishes that swim long distance. Less surface leads to less drag and higher acceleration	

Forked	Found in fishes that are fast swimmers such as predators. Good acceleration and maneuvering	
Emarginate	Found in slow swimming fish. Causes less drag than rounded shape tail.	
Truncate	Found in most fishes. It gives an effective acceleration and maneuvering.	
Rounded	Found mostly in smaller fishes. Larger amount of surface area allows sharp turn to avoid predators	
Pointed	Found mostly in eel species which are relatively slow swimmers as there is less surface area for them to propel.	

Double emarginate	Upper and lower lobes emarginate either with a notch between lobes or they are rounded in the central of the tail	

2.2 Locomotion

Fishes produces thrust by bending its body/caudal fin which is known as (BCF) or by using their median and pectoral fins which is also known as (MPF) (Videler, 2001). BCF and MPF can be broken down into several parts which is the basis of the movement characteristics which is Undulatory motion and Oscillatory motions (P. W. Webb, 1984). Undulatory motion creates wave along the propulsive structure while oscillatory motion causes the fins to swivel without causing wave formation. The connection between this is understood from the diagram as in Figure 2. 3 which was adapted from ((P. W. Webb, 1984). To sum it up these movements cause the fish to accelerate, cruise and maneuvered

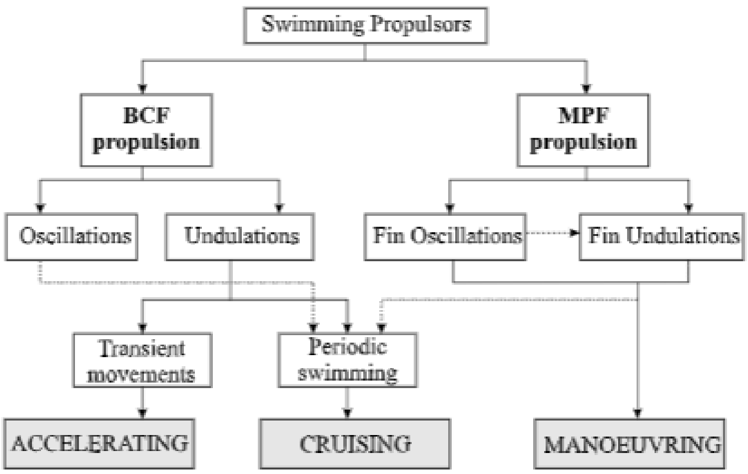


Figure 2.3. Diagram showing the relationship between swimming propulsor and swimming functions. (Adapted from (Paul W. Webb, 1984)

2.2.1 Body/Caudal Fin Propulsion

Body or Caudal fin propulsion (BCF) is the major way that a fish propels through the waters. They create thrust through their tail with a body undulation. The fish body transverse in the opposite direction to the overall movement. Fishes that uses this type of propulsion are mostly predators that swim fast and have higher endurance (Lauder, 2000) for long distance and migration ((Palstra et al., 2009)). There are different types of body actuation that helps these fishes to move around with different body undulation (Gillis, 1997). These types of body undulation are shown in Figure 2. 4. These type of body undulation differs in the wavelenght and the amplitude of propulvive waves developed. A propulsive wave is passed backwards along the fish as it propels into the water . Thus, this generates a force that increases the momentum of the water passing the fish as an equal but opposite direction.

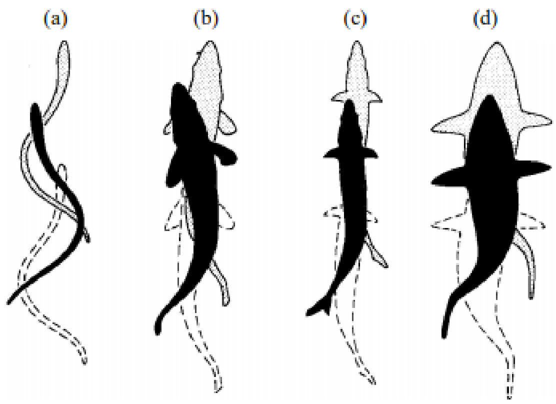


Figure 2. 4. BCF swimming motion a) Anguilliform, b) Subcarangiform, c) Carangiform, d)Thunniform
Taken from (Sfakiotakis et al., 1999)

2.2.2 Angulliform

Augulliform is defined as having the form of an eel or characteristics of an eel ("Definition of ANGUILLIFORM", 2020). Fish that are very flexible and small turning radius fall under this category (Gillis, 1997). Any tendency to recoil is minimized as one complete wavelength as propulsive wave is present. Anguilliformes are capable of swimming backwards as they change the direction of propulsion and as the frequency is high and body movement increases(Wu et al., 2014) . Backwards swimming requires higher body flexibility and lateral displacements. Eels of different types and sea snakes are also included in this category (Gillis, 1997). Figure 2. 5 shows the salamender as the test subject.

Figure 2.5 .Salamader as the subject (Gillis, 1997)

2.2.3 Subcarangiform

Subcarangiform is categorized for fishes that are slightly flexible and with intrinsic muscle. They are quite similar to anguilliform that differentiate them is the side-to-side amplitude that is 1/3 of its body (Lindsey, 1978). The body of this category forms a sinuous path as a form of propulsion through the water (Archer & Johnston, 1989). Cods are one of the fish that can be included in this category (Lindsey, 1978)

2.2.4 Carangiform

Fish in this category are only uses the back end of its body to propel as it is capable of wide flexure. Carangiform fishes are faster and efficient than anguilliform and Subcarangiform (Lindsey, 1978). Fishes such as Salmon and Piranha include this category. These fishes will produce effective thrust as only the trailing edges of the fish produces force thus any other body undulation will waste energy and reduce effectiveness of the thrust produced (Barrett & Triantafyllou, 1999). The turning and the ability for these types of fishes are compromised as they have a rigid body. The tendency for the body to recoil is higher as the lateral forces that is exerted by the fish is concentrated at their posterior. Two main types of adaptation are identified to reduce the recoil forces that act on Carangiform during the research of (Lighthill, 1969). One of the adaptations is to reduce the depth of fish's body where the caudal fin is attached to the trunk. Another one of the finding is to concentrate the mass and body depth to the anterior part of the fish. Figure 2.6 shows the visual representation locomotion of Carangiform that can be referred to understand the adaptations that Carangiform undergo to overcome the recoil effects of its locomotion.

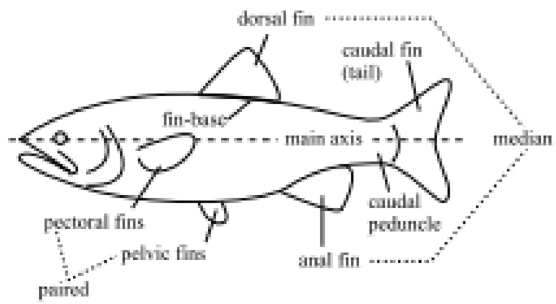


Figure 2. 6: Visual representation of Fish that uses Carangiform locomotion (Sfakiotakis et al., 1999)

2.2.5 Thunniform

Thunniforms are known as the most effective locomotion's in BCF as the movement of the tail creates thrust by lift based method which allows the fishes that has this type of locomotion to cruise at high speed on long period of time. It is often found in predator fish which will only move the last quarter of its body will movie and its body undulation is very limited (Sfakiotakis et al., 1999). The body of Thunniforms are streamlined to reduce pressure drag and the caudal fins are stiff and rigid. Even though the caudal fins of these type of fishes produces high power, the shape and mass distribution of the fish ensures that the recoil on the body is minimized, and sideslipping is induced minimally. Some of the species in this group are warm-blooded as it gives an advantage of endurance and strength for these predators (Guinet et al., 2007). Thunniforms are not suited in slow swimming mode or rapid acceleration from stationary and in turbulent waters. The movement of Thunniforms are shown in Figure 2. 7 and modified from (Fierstine & Walters, 1968). Thus this type of locomotion is used by preadator fishes.

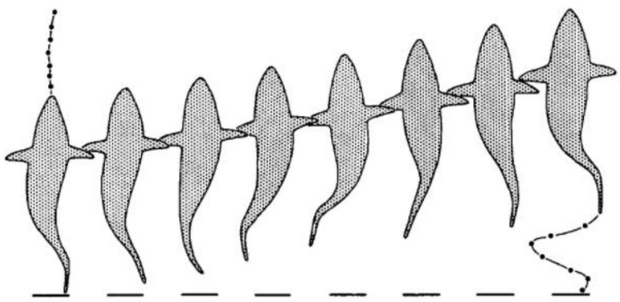


Figure 2. 7. Thunniform swimming of kawakawa Euthynnus affinis

2.2.6 Rajiform

Fishes such as manta ray, and skates uses Rajiform as their locomotion. This type of locomotion is classified under Median or Paired Fin undulation. The thrust for the locomotion of fishes is from its pectoral fin that is very large, triangular most often and flexible. (Sfakiotakis et al., 1999). Undulation of these fishes begin in the anterior part and moves towards the posterior. Fishes that use Rajiform as locomotion propels themselves by creating a propagating wave down from enlarged fins.(Chen et al., 2011) In the Ray family the fins are often flapped up and down. These fishes have adapted to obtain specialized fins that produce thrust and balance torque in steady swimming with these multiple control surfaces. Figure 2.8 shows the pectoral wave and the body kinematics of Rajiform locomotion. This locomotion has a surprising efficiency and maneuverability when used in biomimetic robots. (Blevins & Lauder, 2012). Thus, since the efficiency is high fishes uses low energy to propel through the waters.

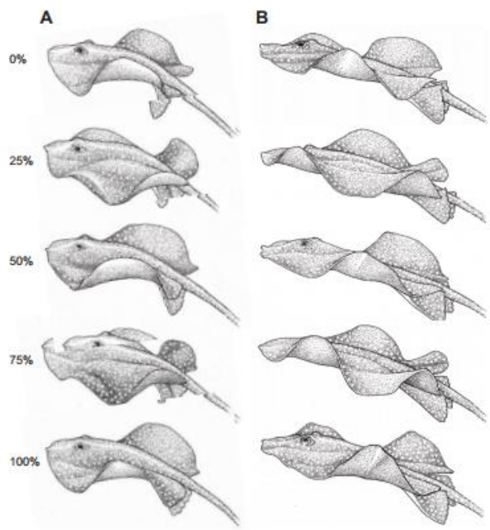


Figure 2.8: Pectoral waves and body kinematics

2.2.7 Diodontiform

Fishes that use this type of locomotion often combines undulation of its fins with flapping movement. (Sfakiotakis et al., 1999). This propels the fish forward to enable it to escape from its predators. This type of locomotion can be seen in porcupine fish.

2.2.8 Amiiform

This type of locomotion is induced by the undulation of dorsal fin. Fishes that use Amiiform locomotion often lack anal and caudal fins and the dorsal fin of these fishes extend along the body length. (Sfakiotakis et al., 1999). Figure 2.9 shows the pectoral and dorsal fins used for Ammiform's locomotion. The characteristic of this fish is found among the seahorses. The dorsal fins of the seahorse can generate many wavelengths that moves across the dorsal fins (Woodall et al., 2012). This enables the seahorse to move forward. However, fishes that uses this locomotion are typically slow in escaping its prey as the undulation of dorsal fin does not give burst trust. In conclusion this type of movement does not have high maneuverability.

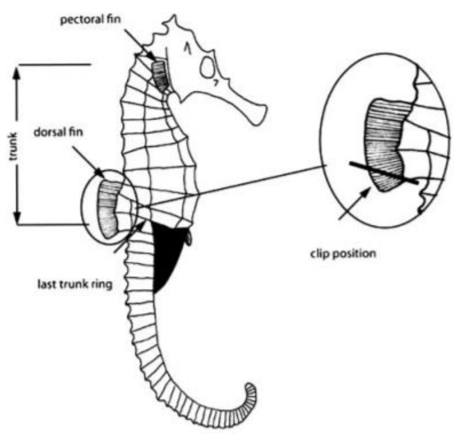


Figure 2.9: Fins used in Amiiform Locomotion (Woodall et al., 2012)

2.2.9 Gymnotiform

Gymnotiforms are the opposite of the Amiiform as they lack dorsal fins and has anal and caudal fins. These fishes held their body straight and rigid when swimming due to the electro sensory system they possess. (Sfakiotakis et al., 1999). The fishes that have this type of locomotion are characterize by having anal fin that move ribbon like. Figure 2.10 shows us how fishes that uses Gymnotiform have a ribbon like movement which was adapted from (Bale et al., 2014). Ribbon like movement is simply the movement of anal fin by undulating it (Whitlow et al., 2019). Thus, this ribbon like movement propels the fishes that uses this type of locomotion through the waters.

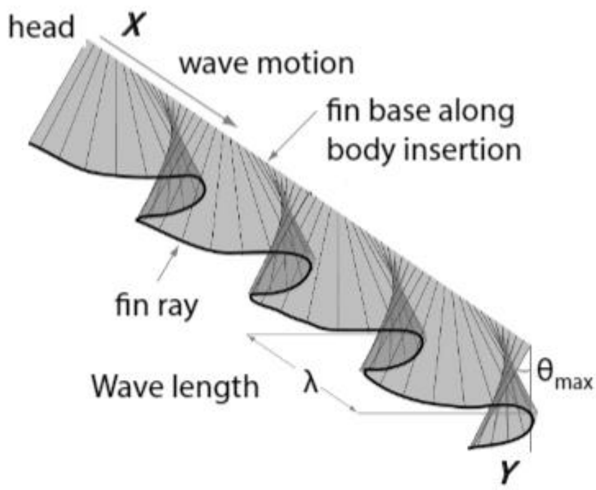


Figure 2.10: Ribbon like movement of Gymnotiform

2.2.10 Balistiform

In this this locomotion both the anal and dorsal fins is used to generate the thrust force. Fishes that use this type of locomotion has a flat and laterally compressed body and median fins that are inclined relative to each other. (Sfakiotakis et al., 1999) The body that these fishes have are mostly ranged from slender and elengated and the median fins has high aspect ratio with posterioly tapered fins (George, 2020). Balistiforms uses its undulation of its median fins by broad ossilation from them. These fishes use their caudal fins to swim at high speed and mdian fins to swim at low speeds.

2. 2. 11 Pectoral fin: Labriform

This type of locomotion is the main swimming mode for many fishes with quite high speed (Walker & Westneat, 1997). Labriform are often found in fishes that live in the coral or reef covered areas as they adapt to their surroundings which includes fishes as Parrotfish and Clownfish. These fishes will only use their caudal fin to escape predators or when their pectoral muscles are at maximum stamina and they have low endurance using their caudal fins (Korsmeyer et al., 2002)

Fish that fall under the category of labriform are difficult to analysis their fin kinematics because of the complicity movement and speed. Rigid rays are present in between the soft membrane of the fins that provides rigidity for the structure ((Aiello et al., 2018)). The flapping motion of these fishes can be divided to 2 categories which is flapping and rowing.

The description of this motion is derived from (Sfakiotakis et al., 1999) as it explains that the leading edge of the fish moves upwards and downwards while other fins membrane remains stiff. This shows that this motion are the power strokes that are done by the fish for close range maneuvering as the resistance increases the speed decreases. In rowing the fin's leading edge is stroked downwards vertically while in upper stroke the fins are pulled back on an angle to the vertical axis. In Figure 2. 11 the motion of flapping and rowing are shown

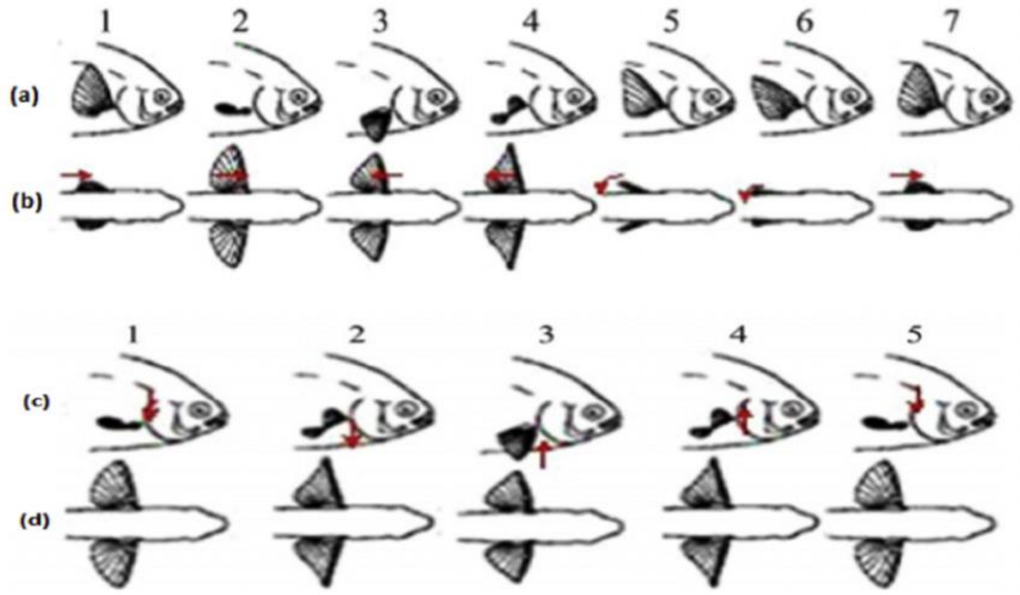


Figure 2.11: Flapping motion modified from (Sitorus et al., 2009) (a) Top view of rowing, (b) side view of rowing, (c) top view of flapping, and (d) side view

2.2.12 Dorsal and anal fin: Tetraodontiform

This type of fish falls under this category as they have 2 paddle fins. 1 dorsal and 1 anal fin for their movement in water (Konno & Furuya, 2005). They make up to 5 percent of tropical aquatic species from the world. Figure 2. 12 shows an ocean Sunfish that can grown up to 1.8 m long and weigh up to 1000 kg. The yaw and pitch control of these fishes are low as these fish have fins that has rigid ribs, and it uses unorthodox oscillation motion to change depth and direction ((Zhu et al., 2019). The rapid undulation of these fishes dorsal and anal fins enables the fishes that uses this locomotion. Caudal fins in these type of fish are reserved for rapid burst of speed. These fishes often have few teeth or a massive beak like tooth plate. Fishes that are categorised in this class include triggerfish, filefishes, boxfishes, Pufferfish and Ocean sunfish. To sum it up Tetraodontiform does not have high maneuverability due to their locomotion.

Figure 2.12 Ocean sunfish

2.2.13 Pectorl, dorsal/anal and caudal fin: Ostraciiform

Fishes that fall under this category can be found in coral reef such as Box fish and Cow fish. They use their pectoral and dorsal fins to move (Chi & Low, 2012). Figure 2. 13 shows a boxer fish which has Ostraciiform as a locomotion. The movement of these type of fishes has a pendulum like oscillation of the caudal fin while the body remains rigid. (Sfakiotakis et al., 1999). The speed at which the fishes move is relatively slow as their body shape is not evolved for high-speed movement (Hove et al., 2001). Thus, the body remains rigid while the caudal fins aids in thrust to aid prey stalking. These fishes can keep a fixtured fin oscillation that helps them in maneuvering in small crevasses. Ostraciiform uses both vertical and horizontal flapping movement when using pectoral fin flapping motion (Hove et al., 2001). Forward thrust and stability is provided by dorsal and anal fin as they flap simultaneously and it uses its small caudal fins to escape predators as it supplies burst propulsion (Hove et al., 2001). In short, all the Ostraciiform has a low hydrodynamics efficiency characteristic.

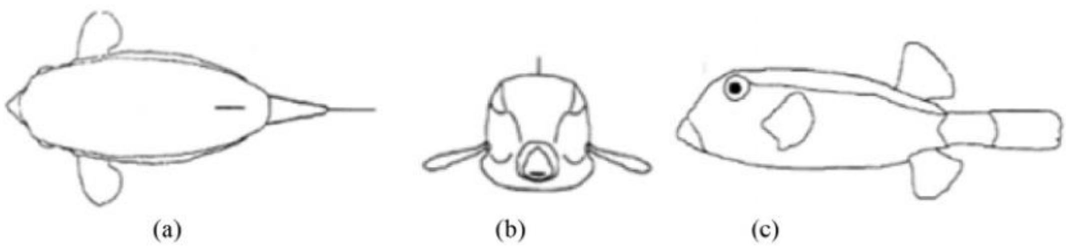


Figure 2. 13: Boxfish: (a) top view, (b) front view, and (c) side view (Hove et al., 2001)

2.3 Mechanism that is involved in fish swimming

Water is incompressible and has a high density which acts as a medium to transfer the movement of fish into locomotion. It is known that density of water is 800 times than air and it counterbalances the gravitation force. Forces involved in swimming of fish are resistance, thrust, weight, and buoyancy with hydrodynamic lift (Figure 2. 14 (a)(J.J. Magnuson, 1978). Fishes also exhibit pitch, yaw, and roll (Figure 2.14 (b)).

Locomotion of the fish is induced by reaction force of the fish's drag, lift and acceleration in the medium. Drag caused by swimming can be divided into several categories such as skin friction between boundary layer of water and fish. Skin friction is formed as a result of large velocity gradient area and the viscosity of the water. Next, pressure is formed as a result of displacing water as the fish passes which causes disruption of water flow around the body of the fish. This s why fishes that swim fast evolved to have a streamlined body. Finally, vortex is formed as the fish generates thrust using its caudal fin which leads to energy lost and drag (Konno & Furuya, 2005). Acceleration or thrust is formed as a result of resistance of water that propels the fish when the velocity of displacing water changes.

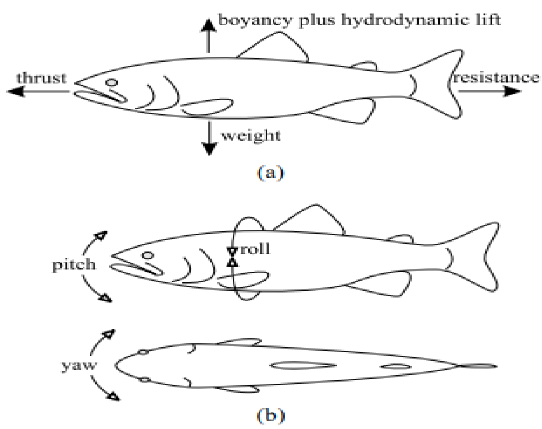


Figure 2.14 (a) The forces action on a swimming fish. (b) Pitch, yaw, and roll (Adapted from (J.J. Magnuson, 1978)

2.4 Vortex formed

The vortex formed by carangiform moving through water is known as Karman Vortex. This vortex is formed because of tail of the body and caudal fin swimmers moving back and forward causing a trail of vortices. (Sfakiotakis et al., 1999). The visual representation of the type of vortex can be seen in Figure 2. 15. The vortex is formed in circular motion which is on the path of swimming of the fish which causes a chain. The motion of the fish is perpendicular to the centre line and the main swirls which causes the vortexs to be combined. (Station, 1959). This vortex is not only formed by fishes but it is also applicable for any type of body under freestream velocity.

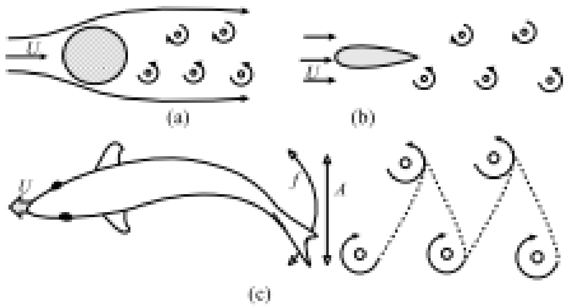


Figure 2.15. The Karman vortex generated by (a) A circular body (b) Airfoil in free stream (c) Fish locomotion (adapted from (Sfakiotakis et al., 1999)