Modeling and swimming performance investigation of a biologically inspired caudal fin propulsion system

Chong, Chee Wee

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**MODELING AND SWIMMING PERFORMANCE
INVESTIGATION OF A BIOLOGICALLY INSPIRED
CAUDAL FIN PROPULSION SYSTEM**

CHONG CHEE WEE

School of Mechanical and Aerospace Engineering

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ABSTRACT

Efficient swimming and maneuvering through water have posed a great challenge to current Autonomous Underwater Vehicles (AUV), as the navigating through water is difficult due the properties of the medium and the external disturbances surrounding it.

Studies have shown that the AUV, which uses propeller, often results in poor swimming efficiency and large turning radius. Investigation into unsteady fish-like locomotion has shown a highly efficient method of propulsion. Although many fish-like vehicles had been designed and developed around the world, most of them had their focus on designing a life-like fish robot for efficiency and maneuverability rather than exploiting the fish locomotion to address on the critical design and control issues. Limited experiment works had been carried out to demonstrate how this fish-like propulsion method could potentially benefit the relevant fields.

A fish-like underwater vehicle (NAF-I) has been developed in this work, in order to carry out in-depth experiments. The aim of this research is to establish a semi-empirical model based on parametric studies, so that a swimming speed prediction equation can be generated for future navigation control. The possibility of drag reduction in an actively swimming bio-mimetic underwater vehicle will also be explored. In particular, we focused on a simple self-propelled fish-like underwater vehicle to demonstrate the potential drag reduction by measuring its swimming speed.

Parametric experimental studies on the bio-mimetic underwater vehicle have been conducted to determine the effect of each parameter on the output thrust force. The relationship between the thrust and swimming velocity has been studied and analyzed. The experimental studies on the effect of the flexible passive spring joint have shown a potential drag reduction.

During the field tests, the fish-like underwater vehicle was able to achieve an average speed of 19.8 meters per minute, which is equivalent to half a body length per second, 0.5 BL/s.

With the basic fundamental hydrodynamic theories and experimental results obtained previously, a semi-empirical scheme has been presented. The predictive models have been developed for the output thrust generated and the swimming velocity of the robot. It can be concluded from the qualitative analysis that the models have been validated in predicting the output thrust and swimming velocity of the fish robot.

With the models being able to adequately predict the output thrust and swimming velocity, we believe that it will be a useful input to future navigation control of the fish robot. Especially in the inertial navigation control, where the sensors input can be compared with this prediction data to reduce its positioning error.

In the future, the system will undergo enhancements to improve its performance based on the experimental analysis. Effective fast-start and turning motion of the bio-mimetic underwater vehicle will be another interesting area to study. Various sensors tested earlier will be incorporated onto the fish robot together with the motion prediction function, to test out its feasibility in an open-loop navigation control.

CHAPTER 1: INTRODUCTION

1.1 Motivation

Efficient swimming and maneuvering through water have posed a great challenge to current Autonomous Underwater Vehicle (AUV), as navigating through water is difficult due the properties of the medium and the external disturbances within it. The demand for AUV to carry out underwater mission has been increasing, so as the sophisticated tasks assigned to it. The current AUV that uses propellers for their main propulsion exhibits in poor performance and efficiency especially under tight conditions (example: space and speed constraint etc). Studies have shown that the AUV which uses such thruster (propeller) often results in efficiency that does not exceed 40% and their turning radius is at least ten times larger than the corresponding value for fish [1]. The use of conventional propeller-typed system also brings a devastating ecological impacts on the marine environment [2]. These systems not only disrupt the underwater ecology, they have also produced undesirable water [3] and noise pollution [4] that places the entire marine's life in risk. These have lead to an increase in interests amongst researchers around the world in developing a highly efficient, better maneuvering and less noise propulsive system, to replace the current thruster used on the AUV. The noiseless propulsive system could also be an additional advantage, particularly for military application where the stealth feature is greatly seeks.

Engineered counterpart or biomimetic [5] of natural locomotion could be the solution of the above addressed concern. Each species has its own unique and optimum way of interacting with its environment, which then dictates the species' body shape, body size, and the way it propels itself, as proposed by Darwinian process of nature selection [6]. Nature selection has ensured that the mechanical systems evolved in fish are very efficient and fitted for their living environments. The body and brain of the fish have evolved in a way that is far beyond the current capability of underwater vehicle. Hence, in order to build an

underwater vehicle with similar capability, we need to understand their physiology and swimming motion.

Studies done on actively swimming dolphin have revealed that streamlining and special behaviors could provide the greatest drag reduction [7]. The understanding of such adaptation used by dolphins has provided insight for the design analogous engineered systems. Many researchers have done a lot of significant works on oscillating foil propulsion [8-14] and have proven that the propulsion and maneuvering mechanisms used by fish have demonstrated a variety of prospective utilities in underwater vehicles.

Based on recent progress in robotics, hydrodynamics of fish-like swimming, new materials, actuators and control technology, more and more research have focused on the development of novel fish-like vehicles [15-20]. Many fish-like vehicles had been designed and developed around the world, but most of them had their focused on designing a life-like robotic fish for efficiency and maneuverability rather than exploiting the fish locomotion to address the critical design and control issues. Little or limited significant experiment works had been carried out to demonstrate how this fish-like propulsion method can potentially benefit the relevant fields.

In this thesis, we will present a fish-like underwater vehicle which being developed with the aim of carrying out a systematic experiment, in order to come out with a semi-empirical models for output thrust and swimming speed prediction to be used for future navigation control. Parametric studies on the fish-like underwater vehicle will be conducted to determine the effect of the various parameters and the relationship between the thrust and swimming velocity. The results collected from the parametric studies will be used as an input for system enhancement and the construction of the semi-empirical model. Through the experiments conducted, we also hope to highlight the possibility of drag reduction in an actively swimming fish-like underwater vehicle. Previous efforts in this area are limited to a towed fish-like underwater vehicle (Robot Tuna,[21]). Here, we have focused on a self-propelled fish-like underwater

vehicle to demonstrate the potential drag reduction. Finally, the plausibility and predictive capability of the models will be assessed both qualitatively and quantitatively by analyzing the trends of the predictive models and by comparing with the experimental results.

1.2 Objectives and Scope

The objectives of the research are to develop a biologically inspired underwater vehicle based on the bio-mimetic study on the swimming gait of fish, and to carry out in-depth experimental study to have better understanding on the factors affecting the swimming performance of the fish robot. The results and analysis from the experimental study will be used to enhance the swimming performance of the fish robot and to construct the semi-empirical models for output thrust and swimming speed prediction.

The following research scope is required in order to achieve the above mentioned objectives:

1. Study the swimming gait of fishes.
2. Develop a suitable modular tail fin mechanism for an underwater vehicle to simulate the swimming motion of the fish, based on the bio-mimetic study.
3. Carry out kinematics study on the tail fin mechanism.
4. Develop the mechatronic system for the robotic fish.
5. Propose a suitable buoyancy system module to be incorporated onto the robotic fish.
6. Carry out parametric studies on the fish-like mechanism to determine how various parameters affect the thrust and performance of the robotic fish.
7. Conduct experiment to demonstrate any potential drag reduction using the developed fish-like underwater vehicle.

-
8. Enhancement of the system will be proposed based on the experiment results and analysis.
 9. Construct the semi-empirical models for the output thrust and swimming speed prediction based on the parametric and motion studies.
 10. Assess and evaluate the semi-empirical models qualitatively and quantitatively.

To focus on the research scope without losing the generality of the proposed work, the following assumptions are made in this present work:

- Hydrodynamic analysis is beyond the scope of this work.
- Only the output thrust generated by the fish-like underwater vehicle and the swimming speed will be analyzed.
- The efficiency of the prototype (NAF-I) will be determined indirectly using the range of Strouhal values, there will be no direct measurement of power input and output of NAF-I.

1.3 Organization of Thesis

The thesis about this research work is divided into six chapters:

Chapter 1 will provide the introduction and motivation to embark on this research.

Chapter 2 will discuss with the reader the existing bio-mimetic technologies and the biological review on the fish swimming locomotion. The gap in this research field will also be highlighted.

Chapter 3 will cover the mechanical and electronic design of the fish-like underwater vehicle. This chapter will feature the process on how the fish-like underwater vehicle came into realization.

Chapter 4 will feature the experiments and field test to determine the co-relation between various parameters and the body velocity using the developed robotic fish as an experimental platform.

Chapter 5 will cover the development of the predictive models and its assessment.

Lastly, Chapter 6 will conclude the work done and proposed future works to be carried out.

CHAPTER 2: LITERATURE REVIEW

2.1 Where It Begins

Natural selection has ensured that the propulsion systems evolved in fish are very efficient and fitted for their living environments. For millions of years, fish have evolved in a way that allows them to swim and maneuver efficiently through water.

Dolphins are one of the most studied marine animals throughout the history. They are considered the fastest swimmer and their capability of leaping over mast of objects have intrigued most people.

The most influential work on swimming dolphin was the drag-reduction mechanism analogy termed by Gray [22]. By comparing the power required to tow a rigid model of a dolphin at a speed of 20 knots with the available estimate muscular power, he found out that the required power to tow the rigid model was seven times larger than the available muscular power (termed as Gray's paradox). He then concludes those dolphins need to employ certain drag-reduction mechanism in order for it to overcome the gap between the muscle power and drag. His conclusion had triggered the studies to determine swimming drag and a search for drag-reduction mechanism. Gray's conclusion has remained controversial over the past 70 years, due to the extreme difficulty in measuring the power/drag in live fish. A review on the drag reduction specific to dolphin [7], done by Fish recently, had shown that the assumption used in Gray's calculation was flawed, due to the inconsistency in calculating drag and underestimation of muscle power of dolphin. However, in his review, Fish concluded that streamline and special behaviors have provided certain forms of drag reduction for dolphin.

Although the assumption used in Gray's calculation was flawed, it has however inspired researchers around the world in coming out a variety of drag-reduction mechanisms based on fish-like swimming motion.

One route towards design a fish-like underwater vehicle that has the same capabilities as a real fish is to understand their body structure and swimming motion. Researchers and engineers have been studying the swimming abilities and performances of fish extensively, hoping that it may provide inspiration for the design of a new propulsive system that will outperform the thrusters (propellers) currently in use.

2.2 Morphology and Fish Swimming Modes

Fish exhibit a large variety of movements, which employ their fins and/or body to produce propulsive, maneuvering and stability force. The classification of swimming movements presented here is originated by Breder's [6] which based on the type of fins and body use to generate the propulsive thrust. Figure 2.1 shows the morphology and the fins of a typical fish that can be employed for its swimming motion.

Figure 2.1 Fish Morphology and Fins used in different Swimming Modes [23]

Breder proposed two swimming modes of fish based on the propulsive structure used: body and/or caudal fin (BCF) locomotion and median and/or paired fin (MPF) locomotion (See Figure 2.2). Fish that generate thrust by bending their bodies to produce a backward-moving propulsive wave that extends to its caudal are classified under BCF locomotion. Those using their median and pectoral fins to generate thrust and propulsive forces are belong to the MPF locomotion.

Figure 2.2 Types of Swimming Modes [24]

From studies, only about 15% of the fish families use non-BCF mode as their routine propulsive means, while a much greater number that typically rely on BCF mode for propulsion employ MPF mode for maneuvering and stabilization [25]. In short, BCF mode is more frequently use when faster speed and large acceleration are involved. In the case of slow movement and fine maneuvering control, MPF is preferred.

In this thesis, we will be focusing on the BCF form of swimming mode because it provides a greater speed and acceleration as compared to MPF mode. As we will be focusing on the performance study and navigation control of the underwater vehicle in the future, the speed and acceleration will play a significant role. In the following section, we will discuss the details regarding the BCF swimming mode.

Body and/or Caudal Fin (BCF) Oscillating and Undulating Mode

BCF Locomotion is further classified into five subcategories, based on the degree of body undulation, as shown in Figure 2.3. The four undulatory BCF locomotion modes reflects not only the changes in the amplitude envelope of the propulsive wave, but also in the way that thrust is generated.

Figure 2.3 BCF Swimming Modes. Shaded Area Contributes to Thrust Generation [26]

In anguilliform mode as shown in Figure 2.3 (a), most or all of the body participates in a side-to-side undulation where the amplitude of the wave is relatively large along the whole body. The body is normally long and thin, with a very low aspect ratio caudal fin. The presence of at least one complete propulsive wavelength during each cycle, minimizes the yawing effect of the body due to the lateral forces. The typical examples of fish that use this type of swimming mode are eel and lamprey. One useful feature of anguilliform will be its ability to swim backward, which simply requires the wave to pass from the head to tail.

Body movements in subcarangiform (Figure 2.3 (b)) swimmers are very similar to anguilliform mode. The main difference is that the side-to-side amplitude of

the undulations are small anteriorly, and expands significantly only in the posterior half or one-third of the body. Trout is an example of a sub-carangiform swimmer.

For carangiform (Figure 2.3 (c)) swimming, the body undulations are further confined to the last third of the body length with its thrust provided by a rather stiff caudal fin. The carangiform swimmers are faster than anguilliform or subcarangiform ones. However, their relatively rigid body has limited their turning and accelerating abilities. Furthermore, there is also an increased tendency for the body to recoil, due to the concentration of lateral forces at the posterior.

Thunniform (Figure 2.3 (d)) mode is the most efficient locomotion mode evolved in the aquatic environment. More than 90% of the thrust is produced at the caudal fin and at the area near the narrow peduncle. The thrust is generated using a lift-based method which allows high cruising speed to be maintained for long period [23]. These fish, including tuna, mackerel and some sharks, have a very well streamline body, narrow peduncles and a tall crescent shaped (lunate) caudal fin. The body shape and mass distribution ensure that the recoil forces due to the power of the thrust force at the caudal fin can be minimized effectively. The thunniform swimmers are designed optimally for high-speed swimming in calm water; they are particularly inefficient for other actions such as slow swimming, turning maneuvers and rapid acceleration from stationary, as well as in turbulent water, due to their relatively stiff body.

The carangiform and thunniform are the swifter swimmers amongst all; hence, it is of no surprise that most studies on efficient swimmer have been focused on these two groups of fish. Extensive studies had been done by Mason and Burdick [27], Kambe [28], Li et al.[29] and Borazjani et al. [30] on the carangiform swimmer, while significant works based on the thunniform mode had also been done by the researchers at MIT [21, 31].

2.3 Biomimetic Robots

Biomimetic is a general term for engineering process and system that mimics biology. People have been trying to copy the nature for a very long time. Animal who have evolved and occupied every environmental niche, provide proven solutions to the problem of navigation, searching and sensing, often in the most difficult area. Biomimetic robots borrow the structure and behaviour from the animals to perform various functions in the real world. Researchers and engineers are able to blend expertise from the fields of biology, biochemistry, mechanical and computer engineering into this emerging field to propose unique solutions once thought to be impossible to achieve. The strides in biological research and the advancement in low-cost, power efficient and compact computer systems are the driving forces to this new philosophy of how a robot is designed.

Robot Fish

In the field of underwater robotics, engineers are trying to mimic various swimming mode of the fish, to come up with a propulsive mechanism that can replace the propeller.

Based on the recent progress in robotics, hydrodynamics of fish-like swimming, new materials, actuators and control technology, more and more research have focused on the development of novel fish-like underwater vehicles [15-21, 33-36]. Figure 2.4 shows the various BCF swimming mode fish-like vehicles being developed by researchers around the world.

The Subcarangiform Essex-G9 and Carangiform Robotuna are of the most well known BCF swimming mode underwater vehicle amongst all the other listed in Figure 2.4.

Figure 2.4 Robotics Fish-like Vehicle based on BCF Swimming Mode being Developed [32].

Essex (G9) robotic fish was made known to most of us with its highly publicize live action at the London Aquarium [16]. This robotic fish was constructed by a research team at the University of Essex led by Professor Hu Huosheng and was funded by the London Aquarium. This robotic fish was designed to swim autonomously like a real fish. However, the current design was built purely for entertainment purpose, as no significant experimental works were conducted on this prototype regarding the swimming performance and the navigation control method.

As for the Robotuna developed by MIT, It was designed and built for research purposes. Their aim was to demonstrate that an actively swimming body would

require less power as compared to a small rigid body being towed at the same speed. Their results had showed that the drag on an actively swimming body was indeed smaller than that of a same rigid body being towed. But, the complexity of their robotic system had overshadowed their purpose of understanding the interaction between the fluid and the fish's body [21]. This is the only significant work, which demonstrates the drag reduction mechanism on a fish-like underwater vehicle concerning actively swimming towed fish-like vehicle. One have to take note that, the experiment was conducted on an actively swimming fish-like vehicle towed by an overhead carrier and not on a self-propelled fish-like vehicle, as it sounded to be. Hence, there is a need to investigate the controversial subject of drag reduction using a more simplified system or method on a self-propelled fish-like vehicle.

Although, there were many fish-like vehicles being developed around the world, but most of them does not have significant experiment results to prove that this new form of propulsive method is indeed better than the current thrusters or to support Triantafyllou finding regarding the drag reduction mechanism [21].

Earlier effort by our team member in building a modular BCF type underwater vehicle (Nanyang Awana, NAW-I as shown in Figures 2.5 (a) & (b) as a research platform had not been successful, mainly due to major design faults. NAW-I tail fin module which provides the propulsive force was designed to be driven by two DC motors (see Figure 2.5 (a)) – motor 1 located in the electronics housing module, which drives joint C, and motor 2, which drives joint A, mounted on the tail fin module [37]. The position where the motor 2 is mounted is a major problem. During operation, when 'motor 1' undergoes oscillation, the moment of inertial caused by the weight of the 'motor 2' is so great that it causes the whole body of NAW-I to yaw (side to side). Due to this undesired yawing, the maximum swimming speed that can be achieved by NAW-I is only up to 4cm/sec (which is equivalent to about 0.08 body length per second, 0.08 BL/s) in laboratory conditions. This speed is far too slow to

conduct any meaningful experiment; hence, there is a need to seek for an alternative design.

Figure 2.5 (a) CAD Model of NAW-I, (b) Actual Prototype of NAW-I tested in Water Tank [37].

Several other fish-like underwater vehicles employing MPF swimming mode which being developed are shown in Figure 2.6. The Nanyang Cutterfish (NCF-1) and Nanyang Knifefish (NKF-II) shown in Figure 2.6 were the first two types of fish-like underwater vehicles developed by our team. As the fish robots developed in NTU are mainly of the MPF type, a natural evolution will be to design and develop BCF propulsion underwater vehicle to allow comparative studies to be performed between the two propulsion modes. Previous effort in developing the BCF type underwater vehicle (NAW-I) does not produce the required results has in turn, provides the author an added challenge in developing a BCF type underwater vehicle.

Figure 2.6 Robotics Fish-like Vehicle based on MPF Swimming Mode being Developed[32].

In this work, a carangiform type of fish-like swimming mechanism will be designed and developed with the aim of carry out in-depth experimental works. Various parametric studies will be carried out to enhance its performance and to construct a semi-empirical model for future navigation control. Moreover, a different method of experiment will be employed to study the possibility of drag reduction in a self-propelled fish-like underwater vehicle.

2.4 Buoyancy Systems

The fish-like underwater vehicle which being designed and developed will also serve as an experimental platform for the studies of navigation and control strategies in the future. Thus, the buoyancy system will be one of the key components for the system, to allow maneuvering of the fish-like underwater vehicle along the vertical axis.

First, we will like to look at how the nature manipulates their buoyancy, and then followed by introducing the existing mechanical counterpart which being

designed, and developed to serve the same function. A suitable system will be selected to be incorporated onto the underwater vehicle.

Since fish live in an environment, which they need to move in three dimensions, buoyancy play a significant role in determining a fish's ability to swim efficiently. If the fish is able to maintain neutral buoyant, it can remain motionless in water without rising or sinking. It allows a fish to spend energy on feeding, escaping predators or mating rather than to maintain its position in the water.

2.4.1 Buoyancy systems in fishes

Most fish obtain neutral buoyant by incorporating air in their body through the use of swim bladder which is a balloon-like organ in the body cavity [38]. The control of the buoyancy at different depth can be achieved by adding or removing the gases from the blood (as shown in Figure 2.7). Lipids are the more common substance used to decrease a fish's density. The incompressibility of lipids prevents them from being vulnerable to the pressure changes. This allows fish to have greater depth variations without the worry of compensating for pressure changes.

Denser fish use their pectoral fins to create dynamic lift, similar to planes and birds. As these fish swim, their pectoral fins are positioned in such a way that to create a difference in pressure, which allows the fish to maintain a certain depth. The two major drawbacks of this method are that these fish must stay moving to stay afloat and they are incapable of swimming backwards or hovering.

Figure 2.7 Natural Buoyancy in Fish [39]

2.4.2 Buoyancy systems in submarine

Submarines can control its buoyancy by changing the amount of water in its ballast tank, thus allowing it to make controlled descents and ascents in water.

As the submarine dives, the air in the ballast tanks is being vented out to allow the water to fill the gap until its overall density is greater than the surrounding water, as shown in Figure 2.8 (a).

To surface the submarine, water in the ballast tank is being forced out by the supply of air that is maintained aboard the submarine in the air flasks. This high pressurize air is used to overcome the high water pressure when the submarine is deeply submerged. Figure 2.8 (b) shows the state of ballast tank when surfacing.

Figure 2.8 State of Ballast Tanks (a) when Submerging, (b) when Surfacing [40]

2.4.3 Buoyancy systems in RC submarine model

The RC submarine models have the ability to navigate through different depths in the water by taking on or pumping out water. This can be accomplished using a piston, inflatable bladder or most commonly through a ballast tank.

Piston concept

Figure 2.9 shows a buoyancy system employing a dual piston in axial alignment. Positive buoyant is achieved by expanding the piston to increase the air displacement volume. Negative buoyant is achieved by contracting the piston to reduce the air displacement volume. This model employs a direct drive coupled to the lead/ball screw to achieve expansion and contraction.

Figure 2.9 Working Principle of Buoyancy Tank [41]

Inflatable bladder concept

Figure 2.10, shows the general layout of a Re-circulating Compressed Air Ballast System (RCABS). This system uses the air inside the cylinder to fill an external bladder, hence changes the buoyancy of the submarine model. A one-way pump mounted inside the cylinder is used to pump the air in the cylinder to the bladder through a hose. The air in the bladder can be returned to the cylinder by a return hose which is connected back to the cylinder through a vent valve. To surface the submarine, the air from the cylinder will be pumped to the bladder-leaving vacuum in the cylinder. To submerge the submarine, the vent valve will be opened to allow the compressed air in the bladder to be transported back to the cylinder. This simple system does not require any external air supply. Thus, it is most widely used in the model submarine.

Figure 2.10 Recirculating Compressed Air Ballast System (RCABS) [42]

Ballast tank concept

This propel ballast tank system is similar to that of the real submarine's ballast tank system. It consists of a ballast tank, an external gas supply and some vent valves. As can be seen in Figure 2.11, the ballast tank has vent holes in the bottom and the top, which can be adjusted to release the content in it. When the top air vent is opened, water can enter the ballast tank through the bottom vents,

hence allowing the submarine model to submerge. To bring the submarine model back to the water surface, the top vent valve will have to be closed before the compressed air from the external gas tank can be vented into the ballast tank to force out the water through the bottom vent.

Figure 2.11 Propel Ballast System Block Diagram [42]

CHAPTER 3: SYSTEM DESIGN OF MECHANISMS AND ELECTRONICS

3.1 Mechanical Design

In this section, the design and implementation of a BCF type fish-like underwater vehicle will be discussed first, followed by the kinematic and motion study on the tail fin mechanism.

3.1.1 Design and Implementation

During the design process, a number of requirements and essential functions of the fish-like underwater vehicle have been identified.

The requirements and essential functions of the fish-like underwater vehicle are as follow:

1. The tail fin mechanism design should be kept as simple as possible while maintaining the ability to perform a BCF carangiform swimming mode.
2. The size of the fish should be less than 0.6m (L) by 0.3 m (W) by 0.4 m (H), to allow mounting on the water-tunnel system for experimental testing.
3. The weight of the fish including all electronic components should not be more than 10 kg for the ease of carrying out the experiment.
4. The robotic fish should be modular in design, allowing ease of modification in the future.
5. The fish should be able to swim at different depth in the water.
6. Waterproofing shall be incorporated onto the fish in a way that allow ease of assembly and disassembly of various modules.

After identifying the requirements and essential functions for the underwater fish robot, several conceptual designs were generated (as shown in Figure 3.1) using the morphological chart. Matrix evaluation table was used to evaluate all the concepts generated.

Figure 3.1 Concept Designs – (I) Robotic Fish with Multiple Servo Joints, (II) Robotic Fish with 4-Bar Linkages Mechanism, (III) Robotic Fish with Cam Drives Mechanism, (IV) Robotic Fish with Linear Actuator Drives

After evaluating all the concepts, the best-rated conceptual design (Concept II) was selected based on the following design criteria:

- (i) high repeatability and reliability
- (ii) fast speed in response
- (iii) ease of maintenance
- (iv) simplicity in design
- (v) effectiveness

The above advantages have caused this design to be selected to go through the embodiment process.

Figure 3.2 shows the CAD model sectional view of a fully assembled fish-like underwater vehicle (NAF-I) after the embodiment design process. All the detail technical drawings of NAF-I can be found in Appendix A.

Figure 3.2 Sectional View of a Full Assembly Robotic Fish

The NAF-I comprises of four main individual modules: tail fin module, electronics housing module, ballast tank module and head module (including sensors and power unit). As these modules are designed in a modular manner, each module can be easily replaced should there be a change in the design or additional functions are required to be incorporated to the robotic fish.

NAF-I uses its caudal fin to provide the propulsion which is a swimming motion commonly employed by carangiform swimmers, such as the arowana or the herring. The caudal fin mechanism is driven by a DC motor with a set of miter gears to convert the horizontal axis of rotation into vertical axis, with the assumption that there are no mechanical losses during the conversion. As shown in Figure 3.2, a prismatic joint with a movable pin can be adjusted to provide an angle different between joint 1 and joint 2, by sliding the pin along the bar. Also, note that the angle of joint 2 depends on the angle of joint 1 and the distance of movable pin from the axis of joint 1.

Detailed explanation about the motion and the kinematic diagram of the tail fin mechanism can be found in Section 3.1.2. Next, we will discuss on the details of the design and functions of the individual modules that make up NAF-I.

Head Module

Figure 3.3 Head Module Design CAD Model

The fish head module as shown in Figure 3.3, will be attached to the front of the electronics-housing module. The main electronic housing (body of NAF-I) may not be suitable for those sensors which are sensitive to noise, due to the present of several D.C motor. Hence, the fish head module was designed to house various sensors, which are sensitive to noise and the battery pack. Moreover, the fish head module was designed in such a way to increase the hydrodynamic properties of the fish-like underwater vehicle, thereby increases its efficiency in propelling itself in the water.

Electronic Housing

The electronics housing module shown in Figure 3.4, shields the electronic components from the harsh underwater environment and acts as a base body where enhancement modules can be mounted. This is also the module where the microprocessor, motor controllers, radio frequency receiver and navigation

sensor for the robotic fish are located. The function of these electronic components will be discussed in Section 3.2.

Figure 3.4 Electronic Housing Design CAD Model

One of the major complaints about the electronics housing designed in previous underwater vehicles was the great amount of screws need to secure the cover to the body. This goes against the embodiment design principal of keeping things simple. One of innovative solutions that this design provides is the use of commercial toggle stainless steel latches to perform the same job. With this simple method, the reduction or even complete elimination of screws will facilitate the maintenance of the robotic fish.

Another innovation in this design is the use of a gasket method. Conventionally, o-rings were used to prevent water from leaking into the electronics body. This design proposed adding a piece of rubber gasket instead of o-rings, a concept commonly found in waterproof plastic food.

Electronic Holder

An electronic holder (Figure 3.5) is use to houses all the electronic components. The electronic holder facilitates the mounting of electronic components and the

loading into the electronic housing. A counter weight driven by a DC motor through a leadscrew is mounted on the electronic holder. The function of the counter weight is to provide titling feature to NAF-I. Thus, even without the present of ballast tank, the NAF-I can still dive into the water by adjusting the position of the counter weight.

Figure 3.5 Electronic Holder Design CAD Model

Ballast Tank Module

A ballast tank (Figure 3.6) is incorporated onto the robotic fish to allow the fish to navigate in the vertical direction. This ballast tank utilizes a single piston (refer to Section 2.4.3) and is driven by a DC motor through a pulley and belt system.

Figure 3.6 Ballast Tank Design CAD Model

Detailed calculation on the estimated buoyancy force of NAF-I can be found in Appendix B.

Caudal Fin Module

Figure 3.7 shows the design of the Caudal Fin mechanism which is driven by a single D.C motor with a set of miter gears to convert the horizontal axis of rotation into vertical axis. The adjustable movable pin and prismatic joint will determine the resultant angle at joint 2. The angle at joint 2 (α_2) can be adjusted by sliding the movable pin along the bar as shown in Figure 3.7. This design allows the author to conduct a parametric study on the effect of joint 2 angles (α_2) of the tail mechanism during the experimental phase.

Figure 3.7 Caudal Fin Mechanism Module

The last joint of the tail fin mechanism is a spring-loaded passive joint, which introduces a certain degree of flexibility to the tail fin mechanism depending on the value of the spring constant. The joint motion is dependent on the spring constant and the drag induced during the course of swimming. Studies have shown that a properly selected chord-wise flexibility can have significant effect on the performance of oscillating foils [9, 43]. Joint 3 (α_3) was designed in such a way that the spring constant can be changed, in order to study the effect of the different degree of flexibility of the caudal fin had on the swimming

performance of the robotic fish. Other than the modules mentioned in this thesis, various other enhancement modules can be developed to be attached to the base body to allow the robotic fish to perform specific functions in the water. There are many possibilities for this modular fish. For example, when the robotic fish is not out in the field performing dangerous military covert operations, it is useful in the research laboratories as a research platform to allow the researchers to study the optimal design of the caudal fin, propulsion methods or even software control algorithms for swarm intelligence based operations underwater.

3.1.2 Motion Study on Tail Fin Mechanism

Figure 3.8 shows the joint motion of the tail fin mechanism with caudal fin. As mentioned earlier, a single D.C motor drives the tail fin mechanism. The angle Joint 1 (α_1) will rotate according to the position of the D.C motor (θ_1). Joint 2 will rotate to an angle (α_2) depending on the angle of rotation at joint 1 (α_1) and the distance of the movable pin position with respect to joint 1 (d). Lastly, the rotational angle of joint 3 (α_3) is dependent on the spring constant and the forces acting on the oscillating caudal fin underwater. Hence, this tail fin mechanism is a two degree of freedom system with one active joint (α_1 , which driven by the D.C motor) and one passive spring joint (α_3 , which driven by the reaction forces acting on the caudal fin when the tail fin is oscillating). The degree of freedom (DOF) for the tail fin mechanism can also be determined by using the modified Gruebler's equation [44] for planar motion mechanism as shown in Equation (3.1).

$$DOF = 3(n_L - 1) - 2n'_j - n''_j \quad (3.1)$$

where n_L : number of links

n'_j : number of 1 DOF joints

n''_j : number of 2 DOF joints

Figure 3.8 Tail Fin Mechanism showing the Joints Motion

As mentioned earlier, the tail fin mechanism has a spring-loaded passive joint 3. Normally, a spring is considered to have a 3 DOF when connected between two links with both end pinned. But for this case, it can be modeled as a linear actuator since the spring is pinned between two revolute joints (refer to Figure 3.8, X1 and X2) and the links of these two revolute joints are constraint to move in one direction only (refer to Figure 3.9 a). Hence, there will be seven links (n_L), eight '1 DOF' joints (n_j') and zero '2 DOF' joints (n_j'') for this mechanism. The DOF of the tail fin mechanism can be obtained by substituting this value into Equation (3.1) as shown below:

$$\begin{aligned}
 DOF &= 3(n_L - 1) - 2n_j' - n_j'' \\
 &= 3(7 - 1) - 2(8) - 0 \\
 &= 18 - 16 \\
 &= 2
 \end{aligned}$$

From the calculation above, the degree of freedom (DOF) for the tail fin mechanism was found to be two which is what as expected from earlier study.

After determining the DOF and the input joints for the tail fin mechanism, the position and angle of any point on the tail fin mechanism can then be determined and expressed in terms of the input parameters (α_1 , d and α_3).

First, we will look at input joint 1 (referring to the left-hand half of the kinematics diagram of the tail fin mechanism shown in Figures 3.9 a and b).

$$n_L = 7$$

Link 5 & 6 = Kinematic equivalent of a spring

Figure 3.9 Kinematics Diagram of the Caudal Tail Fin Mechanism

By using simple trigonometry, the angle of joint 2 (α_2) in terms of α_1 and the distance ' d ' can be determined as shown in Equation (3.2).

$$\begin{aligned}
 O &= l \sin(\alpha_1) \\
 d + M &= l \cos(\alpha_1) \\
 M &= l \cos(\alpha_1) - d \\
 \alpha_2 &= \tan^{-1}(O/M) \\
 \alpha_2 &= \tan^{-1} [(l \sin \alpha_1)/(l \cos \alpha_1 - d)]
 \end{aligned} \tag{3.2}$$

From Equation (3.2), it can be noticed that the rotation angle of joint 2 (α_2) will increase as the distance d and α_1 increases (Note: ' l ' is a constant and is referring to length of link 1).

Also by trigonometry, the sweeping amplitude up to joint 3 (Q) was found to be:

$$\begin{aligned}
 Q &= O + cg(\sin \alpha_2) \\
 Q &= l \sin \alpha_1 + cg(\sin \alpha_2)
 \end{aligned} \tag{3.3}$$

Note that ' l ' (Link1) and ' cg ' (part of link 2, revolute joint c to g) are constant. By substituting Equation (3.2) into Equation (3.3), we will have Q expressed in terms of α_1 and d .

$$Q = l \sin \alpha_1 + cg \left[\sin \left(\tan^{-1} [(l \sin \alpha_1)/(l \cos \alpha_1 - d)] \right) \right] \tag{3.4}$$

Next, we will look at the right-hand half of the kinematics diagram (refer to Figure 3.9 b) where the second input (T_2) lies. This passive input torque at joint 3 is caused by the reaction forces acting on the surface area of the caudal fin during oscillation. Its rotating angle (α_3) is depending on the spring constant and the force acting on the caudal fin. Therefore, if the angle (α_3) is known, the force acting on the caudal fin can be found, since the moment caused by the force acting on the caudal fin tail should be equal to the reaction moment generated by the spring force ($F_s = kx$, where ' k ' is the spring constant and ' x '

is the additional spring length due to the tension force). By referring to the kinematics diagram, the additional tensioned spring length (x) can be expressed in terms of the angle, α_3 as shown below:

Applying Cosine rule on Triangle 'efg'

$$\begin{aligned}
 (ef)^2 &= (fg)^2 + (eg)^2 - 2(fg)(eg)\cos\alpha_3 \\
 ef &= \sqrt{(fg)^2 + (eg)^2 - 2(fg)(eg)\cos\alpha_3} \\
 ef &= ei + fi \\
 ei + fi &= \sqrt{(fg)^2 + (eg)^2 - 2(fg)(eg)\cos\alpha_3} \\
 fi &= \sqrt{(fg)^2 + (eg)^2 - 2(fg)(eg)\cos\alpha_3} - ei \\
 fi &= x
 \end{aligned}$$

SpringForce, $F_s = kx$

$$\begin{aligned}
 &= k(fi) \\
 &= k\left(\sqrt{(fg)^2 + (eg)^2 - 2(fg)(eg)\cos\alpha_3} - ei\right)
 \end{aligned}$$

or

$$\alpha_3 = \cos^{-1} \left[\frac{(fg)^2 + (eg)^2 - \left(\frac{F_s}{k} - ei\right)^2}{2(fg)(eg)} \right] \quad (3.5)$$

With α_3 known, the sweeping amplitude of the tip-end (j) can be expressed as

$$R = Q + gj[\sin(\alpha_2 - \alpha_3)] \quad (3.6)$$

where 'gj' is the length between point g and j (refer to Figure 3.9 b)

The proposed tail fin mechanism was simulated using ARTAS - Mechanical Design Software, SAM 5.1 (Simulation and Analysis of Mechanism)[45]. The

results from the simulation (Figure 3.10) show that the mechanism is workable and is also tally with the theoretical results obtained from Equation (3.2).

Figure 3.10 Simulated Motion of the Proposed Tail Fin Mechanism using SAM.

Figure 3.10 shows the simulated motion of the proposed tail mechanism in one complete cycle. As can be seen, the mechanism is symmetric for the upper half and lower half cycle. Please note that the joint 3 motion which simulated using SAM is according to define spring constant, the actual motion of joint 3 can be found through experiment by measuring the spring force or the angle of rotation of joint 3 for each given set of parameter.

Figure 3.11 Result from SAM Analysis, showing the Effect of Movable Pin Position had on the Joint Angle α_2 .

By comparing the two graphs and the path of tail fin mechanism in Figure 3.11, we can notice the significant changes in the angle of joint 2 (α_2) as the distance

between the movable pin and joint 1 increases (from 39 mm to 54mm). Note that α_1 and α_2 are always in phase. This result shows that the rotation angle of joint 2 (α_2) can be increased by increasing the distance ' d ' and it tally well with the result from the theoretical calculation using Equation (3.2).

3.2 Electronic and Software Control

3.2.1 Control Architecture

The electronics system is created to control the fish robot's locomotion in the water. Once the electronics system has been established, software algorithms can be designed to control the motion of the robotic fish in the water.

The electronic system of the fish robot is formed by integrating various electronic components together to provide the required functions and control. It was designed using a modular concept; hence, additional enhancement module can be added with ease in the future. Figure 3.12 shows the control architecture of the NAF-I, which is formed by integrating various electronic components together to provide the required motion and control. The control system consists of the following modules: the master controller, the radio frequency (RF) transceiver, motor (local) controllers and navigation sensors.

Figure 3.12 Proposed Control Layout of Electronic System

The fish robot NAF-I is remotely controlled by using the Graphic User Interface (GUI, shown in Figure 3.13) installed on a personal computer. The GUI allows the user to set the required frequency and amplitude of oscillation, change the PID setting, control the swimming direction and the vertical movement (the counter balanced weight and the ballast tank) of the robotic fish. A pair of transceivers forms the communication link between the personal computer and the fish robot. The signal received by the fish robot is first processed by the master controller and then distributed to the respective local controller through I²C protocol, to perform the required tasks.

Figure 3.13 User Interface use to Control the Fish Robot Remotely from a Personal Computer.

3.2.2 Electronic Control Board

Figure 3.14 Electronic Control Board with various Units Integrated.

Master Controller Module

The master controller module acts as a brain of the fish robot. This is achieved by having a microprocessor to process the various signal inputs received by the fish robot and perform decisions based on these inputs. The PIC18F-4431 microprocessor was chosen to be used in currently design. This is because it has a fast processing time, integrated Analog to Digital Converted (ADC), multiple Pulse-Width Modulation (PWM) output pins and allows multitasking. All these features are important for the control of the fish robot.

Radio Frequency Module

Two Radio-Frequency transceivers (ER400TRS-02) were selected to form the communication link between the fish robot and the user control station (personal computer), due to its high transfer rate and small packaging size. However, there is a limitation of using RF systems for underwater communication. When the fish robot is too deep into the water, it will not be able to receive/transmit signals as per normal. This limitation is due to the attenuation effects of the radio wave through water. However, this is not an issue, as the fish robot is not expected to swim more than one meter below the surface.

Motor (Local) Controller Module

The D.C. micro motors can be controlled using an H-bridge chip (LMD-18200) paired with a based processor (PIC18F-2431). The LMD-18200 is capable of driving 6A peak, or 3A continuous load.

The Motor (Local) controller module is a PID closed-loop servo motor controller. It uses quadrature encoder feedback to precisely controller the position, speed, and acceleration of almost any motor. More details about the PID control will be discussed in the next section.

3.2.3 Software Control

Software program is needed to process the data received, make necessary decision and generate the output signals to be send to the hardware. The robotic system will not be able to function correctly without it, even if all the hardware is present.

One of the most important issues to overcome during the development of the software is the communication protocol to be used between the microprocessor

and the motor controller. If the communication link is not established properly, the robotic system will not function.

I²C Protocol

This protocol allows up to eight slave motor controllers to be controlled by using only two I/O ports from the microprocessor.

Figure 3.15 I²C Serial Bus [46]

I²C is a two-wire serial bus (Figure 3.15), which was originally developed by Philips for communication between devices inside a TV set. There is no need for chip select or arbitration logic, making it cheap and simple to implement in hardware. In addition, it is compatible with the model of PIC chips we have selected to be used on the fish robot's control system.

The two I²C signals are serial data (SDA) and serial clock (SCL). Together, these signals make it possible to support serial transmission of 8-bit bytes of data-7-bit device addresses plus control bits-over the two-wire serial bus. The device that initiates a transaction on the I²C bus is termed as master, which in this case, is the microprocessor. The master normally controls the clock signal. A device being addressed by the master is called a slave.

Each I²C-compatible hardware slave device comes with a predefined device address, the lower bits of which may be configurable at the board level. The master transmits the device address of the intended slave at the beginning of every transaction. Each slave is responsible for monitoring the bus and responding only to its own address. This addressing scheme limits the number

of identical slave devices that can exist on an I²C bus without contention, with the limit set by the number of user-configurable address bits.

I²C was chosen as it offers good support for communication with on-board devices that are accessed on an occasional basis. I²C's competitive advantage over other low-speed short-distance communication schemes is that its cost and complexity do not scale up with the number of devices on the bus. With its built-in addressing scheme and straightforward means to transfer strings of bytes, I²C is an elegant, minimalist solution for modest, "inside the box" communication needs.

Motion Control of Tail Fin Mechanism

The tail fin mechanism will execute a sinusoidal motion as described by the equation below:

$$\alpha_1(t) = \theta_{offset} + \theta_1 \sin(2\pi ft) \quad (3.7)$$

where α_1 is the angle between the first segment of tail fin mechanism (ac , refer to Figure 3.9 b) and the neutral axis, θ_{offset} is the offset angle of the neutral axis from its original position, θ_1 is the input amplitude to the motor, and f is the oscillating frequency of the tail fin mechanism. Note that the tail fin will always oscillate symmetrically about the neutral axis. θ_{offset} is mainly meant for controlling the swimming direction of the fish robot.

Once the communication protocol is established, the motion of the motor can then be controlled using classical control method like PID control.

All the input parameters (f , θ_1 , and θ_{offset}) were sent through the pair of transceiver to the master controller for processing, thereafter the control signal is being sent to the motor (local) controller to execute the prescribed motion of the tail fin.

Figure 3.16 shows the general closed loop control for the tail fin mechanism, where θ_{Input} (tail fin input angle) is the input sinusoidal motion as given in Equation (3.7) and θ_{Output} is the output sinusoidal motion of the tail fin mechanism based on the control function.

Figure 3.16 A General Closed Loop Control for the D.C Motor

The motor (local) controller uses a PID (Proportional, Integral, and Derivative) algorithm to calculate how much power to deliver to the motor, and in which direction. This is not a new technique. It was developed in the 1960's, and is still the accepted standard today for fast, accurate motion control, as well as most other types of control systems.

$$\text{PID} = K_p + K_i \frac{1}{s} + K_d s \quad (3.8)$$

Equation (3.8) for PID control has three major components, the sum of which equals the power to be delivered to the motor. The inputs to the equation are the set point ("setPosition" register), the actual position ("mPosition" register), and the three key constants, K_p , K_i , and K_d , the proportional, integral, and derivative constants, respectively.

The error, "ε" can be calculated by subtracting the set point from the actual position:

$$\varepsilon = \theta_{Output} - \theta_{Input} \quad (3.9)$$

The Proportional component is thus:

$$K_p \times \varepsilon$$

The Integral component is calculated based on the integral over time of the error:

$$K_i \times \int \varepsilon dt$$

The Derivative component is calculated based on the differentiating the actual position over time, which in the case of motor control is the same as the velocity (“*mVel*” is the velocity register variable used in the program):

$$K_d \times mVel$$

So the resulting equation that is sent to the motor is:

$$mPower = K_p \times \varepsilon + K_i \times \int \varepsilon dt + K_d \times mVel \quad (3.10)$$

The open-loop model of the system (motor-linkage system) is defined as:

$$\frac{K}{s(s + 1/\tau)}$$

where, K is the gain of open-loop system, which is a standard control model [47] given by:

$$K = \frac{K_m k_G}{RJ} \quad (3.11)$$

On the other hand, τ , is the mechanical time constant of the system given by:

$$\tau = \frac{RJ}{bR + K_m^2} \quad (3.12)$$

Note that the damping coefficient, b (drag force exerted by water on the caudal fin) is proportional to the velocity of the caudal fin [48]. The values of the constant can be found in Table 3.1.

Table 3.1 Maxon D.C Motor Physical Constant

Values at Nominal Voltage	
Nominal Voltage U (V)	15
Torque constant K_m (mNm/A)	14.3
Terminal Resistance R (ohm)	0.902
Terminal inductance L (mH)	0.0882
Rotor Inertia J (gcm ²)	87.3
Nominal Gear Ratio k_G	$180/\pi/103$

The values (K_p , K_d and K_i) for the PID control were determined experimentally. The fish robot was mounted in the water tank and set to oscillate at a given amplitude and frequency. The output signal from the motor encoder was captured and plotted with the input signal for comparison. By trial and error, the optimal values for the PID constant were found to be 320, 2.00 and 0.02 for K_p , K_d and K_i respectively.

Figure 3.17 Input Signal versus the Output Signal using the PID Control (with Amplitude, $\theta_1 = 12$ degree, Frequency, $f = 2$ Hz which corresponds to a period of 0.5 second).

Figure 3.17 shows an example of how well the output signal follows the input signal with the PID constant found. The phase of the output signal follows very well with the input signal, but not for the amplitude. Hence, during experiments, the input amplitude will be offset to higher value, so the resultant output amplitude will turn out to be the desired value.

3.2.4 Testing and Evaluation of Sensors

Navigation Sensors

The digital compass, pressure sensor, accelerometer and the sharp sensor make up the primary navigation system of the fish. This primary system will be interfacing with the more advances acoustic and vision system in the future.

Digital Compass Sensor

Figure 3.18 Devantech CMPS03 Digital Compass

A digital compass CMPS03 (Figure 3.18) is used to assist the fish in following particular direction. This compass module uses either a Pulse-Width Modulation (PWM) output or the I²C bus for communications. The CMPS03 module is mounted horizontally on a custom PCB inside the fish head and is interfaced with the BX-24 Stamp using the PWM signal.

Figure 3.19 shows the circuit schematic for connecting compass module to the BX-24 stamp using PWM signal. The PULSIN command used to retrieve the PWM signal have different timing depending on the type of stamp used. For this case, a BX-24 having a resolution of 1.08 μ s is used. A simple calculation is needed to convert the PWM signal received into required output (provides a resolution of 0.1 degrees). The output signal from the BX-24 will be passed to the master controller (PIC18F4431, see Figure 3.12) for further processing.

Figure 3.19 Circuit Schematic for connecting BX-24 to the CMPS03 Module using PWM

Accelerometer

Figure 3.20 Memsic MX2125 Accelerometer

The MX2125 (Figure 3.20) is a micro-accelerometer offered by MEMSIC. Instead of sensing the capacitive change in the micro-mass commonly found in most other designs, MX2125 utilizes a tiny temperature sensor to sense the change in temperature within the small volume of gas placed at the center of the chip. With no acceleration imposed, the temperature sensors will sense the same temperature, i.e. have the same readings; upon acceleration, the heated section of the gas will be displaced by virtue of convection, causing the temperature

sensors at opposing ends to have a difference in reading. A built-in electronics translates the state of acceleration in the manner of a square-wave output.

A sampling of possible Basic Stamp module applications with the Memsic 2125 includes:

- Dual-axis tilt sensing for autonomous robotic applications
- Single-axis rotational position sensing
- Movement/Lack-of-movement sensing for alarm systems
- R/c hobby project such as autopilots

For the present design, the MX2125 accelerometer is mounted horizontally inside the electronics box and provides a PWM signal that is corresponding to the tilt on a particular axis. The BX-24 Stamp reads the signal in using the PULSIN command. The circuit schematic for Memsic 2125 is shown in Figure 3.21. The accelerometer will be mounted at the fish robot's centre of gravity (above the tail fin motor, see Figure 3.5) with the X-Y plane parallel with the electronic housing cover (see Figure 3.4) and the Y-axis in the direction of the fish robot's head.

Figure 3.21 Essential Memsic 2125 Connection

Pressure Sensor

Figure 3.22 Omega Solid State Pressure Transducer PX219 Series

OMEGA PX219 Series general-purpose pressure transducers (Figure 3.22) are accurate, highly reliable pressure transducers suitable for the harshest industrial environments. The small size and lightweight of the PX219 Series pressure sensors make them ideal for tough vibration and shock environments. The unusually high performance of this solid-state pressure transducer comes from the 4-active-arm-bridge sensor using a micro-machined diffused silicon diaphragm and proprietary thin film media and dielectric isolation barriers. A proprietary thin film media provides excellent temperature compensation from -20 to 80 °C (-4 to 176 °F), and very tight tolerances for zero balance and span. Packaged in stainless steel housing, PX209 pressure transducer has excellent shock and vibration performance and the wetted parts are impervious to almost all industrial liquids and gases.

The pressure sensor PX219-015G5V is mounted outside the electronic box and the cable is properly sealed to IP67 standard. The pressure sensor can take measurement between 0 Psi to 15 Psi and provides a linear analogue voltage output from 0 to 5 volts proportional to the pressure. This sensor is connected to the microprocessor ADC input pin in order to monitor the depth that the fish attains as shown in Figure 3.23.

Figure 3.23 Circuit Schematic for PX219 Pressure Transducer

Sharp™ Sensor

This Infra-Red (IR) sensor from Sharp™ (Figure 3.24) takes a continuous distance reading and reports the distance as an analog voltage with a distance range of 10cm to 80cm. It is mounted inside the fish's head compartment.

Figure 3.24 Sharp GP2D12 General Purpose Distance Measuring Sensor

Its purpose is to detect obstacles underwater and provides feedback to the microprocessor (PIC18F-4431), thus allowing the fish to avoid obstacle.

Sharp™ Sensor Testing

In order to move in an unstructured environment, the fish robot must first be able to avoid obstacles in its path of motion. An infrared sensor (GP2D12) developed by Sharp™ sensor was incorporated onto fish robot to allow it to navigate over obstacle. Experiment has been performed on this sensor to test its underwater sensing range and suitability for underwater application. The sharp sensor is mounted inside a transparent waterproof box and placed into a water tank. The signal from the sharp sensor is processed using a PIC18F-4431 micro-processor and output on the computer screen using RS232 cable. The results on different medium (air, clear water, dilute green tea (Figure 3.25 (a)) and concentrated green tea (Figure 3.25 (b)) were recorded and tabulated in an excel sheet.

Figure 3.25 (a) Dilute Green Tea (b) Concentrated Green Tea

Figure 3.26 shows the comparison of the sensor output signal in different medium. From the graph, we can see that the maximum sensing range of the sharp sensor decrease significantly from air (80cm) to clear water (45cm). Moreover, from clear water to dilute green tea, the maximum range drops for another 17 cm to around 27 cm. As for the concentrated green tea, the maximum sensing range is approximately 23 cm.

Hence, the sharp sensor is feasible for implementing onto the fish to provide obstacle avoidance. It was mounted inside the head module of the fish (refer to Figure 3.3).

The digital compass sensor, accelerometer, pressure sensor and the infrared sensor will be incorporate onto the fish robot for future navigation testing..

Figure 3.26 Sensing Range under Different Medium (by using Sharp™ Sensor)

3.3 Summary

A modular BCF type bio-mimetic fish robot had been designed and developed using mechatronics principles. Structurally, it should be capable of conducting sea trial operation down to a depth of 3m and up to 4 hours operation time inclusive of standby.

Several innovative solutions were proposed during the design stage to enhance the waterproofing capability of the fish robot. In particular, the gasket and toggle latch combination proved to be so robust and easy to use that it has become the de facto standard in designing future waterproofing casing for housing the electronic circuitry. The combination of rubber seal and normal switches has also facilitated the ease of turning on/off the fish robot without having the trouble to dismantle any module.

The communication protocols used between the microprocessor, the motor controller and communication module had been established. The communication link between the fish robot and the user control station was formed up with the use of two radio-frequency transceivers. Hence, the fish robot can be controlled wirelessly by using the Graphic User Interface (GUI) being developed.

The feasibility of various sensors have been evaluated and will be incorporated onto the fish robot (NAF-I) for future navigation control and testing.

CHAPTER 4: TESTING AND EVALUATION OF PROTOTYPE

In the following sections, we would discuss about the various experiments being conducted using the carangiform fish-like underwater vehicle (NAF-I) that had been developed. The experiments were conducted at the water tunnel laboratory and diving pool of Nanyang Technological University.

Firstly, the specification of the NAF-I and the water-tunnel experimental setup will be presented, followed by the experiment and analysis on the rigid body drag. Thereafter, a statistical analysis on the significance effect of various parameters on the output thrust generated will be discussed [49]. Lastly, the experiment regarding the relationship between the net thrust generated and the swimming speed (fixed and free body motion) of the NAF-I will be presented with the initial field test result at the Nanyang's pond.

4.1 Specification of Prototype

The prototype used in the experiment and the field test is as shown in Figure 4.1. The relevant specifications of the fish robot are tabulated in Table 4.1.

Figure 4.1 Fully Assembled Fish-like Underwater Vehicle

Table 4.1 Specification of NAF-I

Mass	Approximate 6.8 kg
Dimension	661mm (L) x 260mm (H) x 100mm (W)
Actuator	2 units of Maxon DC Micromotor
Microcontroller	PIC18F-2431
Power source	15VDC, 4000mAH Ni-H battery
Swimming speed	0.33 m/s, ½ BL/s (max)
Swimming mode	Straight, turning, diving and surfacing
Turning radius	0.1 m
Operating time	Approximately 4 hours (fully charged)
Communication method	FM radio frequency

4.2 Experimental Setup and Force Definitions (Water Tunnel Laboratory)

4.2.1 Experimental Setup

The experiment conducted at the water tunnel laboratory is being carried out in the water tunnel system equipped with a water pump (which can provide maximum speed of 50Hz, 0.17m/s linear velocity at the test section), a tempered glass test section, an electronic flow control panel and array of screeners to provide the laminar flow. The schematic layout of the water tunnel is shown in Figure 4.2.

Figure 4.2 General Layout of Water-tunnel System [50]

An ATI Gamma six axis load cell transducer was used for recording the forces produced by the fish-like underwater vehicle.

Figure 4.3 shows the actual setup of the fish robot prototype in the water-tunnel test section. The arrangement of axes for the force transducer is as follow:

X-axis: The positive x-axis is aligned in the forward swimming direction of the fish robot. The force measured is the resultant net force (thrust/drag) generated by the oscillating caudal fin along the X-axis.

Y-axis: Aligned perpendicular to the axis of the forward motion (into/out-of paper) where the side force generated by the oscillating fin along the Y-axis is captured.

Z-axis: Aligned in the vertical direction to measure the resultant force (positive/negative buoyant) along the Z-axis.

Figure 4.3 NAF-I mounted on the Test Section of the Water-tunnel.

Both the reaction forces and torques generated by the oscillating fin are recorded using the software provided by ATI.

This setup is identical for all experiments conducted in the water tunnel system, but the way the forces are being measured/captured are different for each experiment. We will introduce the force being measured for each experiment before going into the detailed discussion, in order to avoid any misinterpretation.

The following experiments will be conducted:

- a) Experimental studies on the drag of the rigid body (Section 4.3).
- b) Parametric studies (Section 4.4 and 4.5)
- c) Experimental studies on the thrust-speed relationship (Section 4.6).

Note: Due to the symmetry of the oscillating caudal tail fin during operation, the boundary effect from both side of the water-tunnel wall will be cancelled off. Hence, we assumed that the effect from the side walls to be negligible. However, the blockage effect will be considered and the flow velocity under various cases will be adjusted accordingly.

4.2.2 Force Definitions

The forces being measured by the x-force transducer under various conditions are summarized as follow:

- i.) With water flow rates, but no tail motion, the x-force transducer will measure the body drag force, F_{bd}

$$F_x = F_{bd}$$

- ii.) With no water flow (zero flow rate), but with tail motion, the x-force transducer will measure the net force of the thrust, T_{tail} produced by the tail and the drag induced by the tail motion, F_{td}

$$F_x = F_{tail} = T_{tail} - F_{td}$$

-
- iii.) With water flow rates and with tail motion, the x-force transducer will measure the net force of the thrust produced by the tail and the drag forces induced by the tail motion and the body drag force

$$F_x = F_{x\text{-system}} = F_{tail} - F_{bd} = T_{tail} - F_{td} - F_{bd}$$

4.3 Experimental Study on the Drag of the Rigid Body

With the experimental setup in place, the first experiment was to determine the relationship between the rigid body drag of NAF-I and the water tunnel flow velocity, as this result will be significant for future analysis and studies, especially in identifying the potential drag reduction with this type of propulsive method.

4.3.1 Nature of Force Measured

NAF-I was mounted in the water-tunnel according to the setup as discussed in Section 4.2. The force sensor is being biased to zero after the water in the tank (no flow) had been stabilized. Thereafter, the water-pump will be turned on and set to a frequency of 10 Hz. We waited for the flow in the water-tunnel to stabilize (approximately 5 minutes for the system to stabilize) before recording the force sensor values. Three readings will be taken from the force sensor for each particular run for better accuracy. The mean value from the three readings is taken to be the rigid body drag of that run. The experiment was repeated for the water-pump frequency of 20, 30, 40 and 50 Hz.

4.3.2 Result and Analysis

The corresponding drag force for each frequency is being recorded and plotted as shown in Figure 4.4. Note that the relationship between the water-tunnel

pump frequency (Hz) and the water-tunnel flow velocity (m/s) is approximately linear and is defined as:

$$\text{Water-tunnel flow velocity (m/s)} = 0.0034 * \text{Water-tunnel pump (Hz)} + 0.0008$$

With this relationship, the rigid body drag is plotted against the water-tunnel flow velocity as shown in Figure 4.4. As can be seen from the chart, the drag force of the rigid body can be considered to have a quadratic relationship to the water-tunnel flow velocity. By using the trend line function in Excel spreadsheet, an equation relating the rigid body's drag to the water-tunnel flow velocity was found as shown in Figure 4.4. Thus, the pure drags force of the rigid body (F_{bd}) in terms of the water-tunnel's flow velocity can be expressed as:

$$F_{bd} = -2.3548 v^2 - 0.487v + 0.0017 \quad (4.1)$$

Figure 4.4 Drag of Fish Robot's Body against the Water-tunnel's Flow Velocity (Flow Condition: Laminar to Transitional Flow).

4.4 Significance of Controlled Parameters

4.4.1 Design of Experiment (DOE)

A set of experiments is designed to evaluate the performance of NAF-I. The six parameters (frequency (f), amplitude (θ_1), movable pin position (D), aspect ratio (r), spring constant (k) and water-tunnel flow velocity (v)) which were thought to have effect on the swimming performance of the fish robot were considered during the experiments. Note that the aspect ratio (r) is defined by H^2/A , where H is the vertical height between the two tip ends and A is the area of the fin surface (refer to Appendix D for more detailed).

When selecting the levels for those parameters, the prototype capability, force transducer limitation and the range of practical application were considered. For example, three spring constants (k) were considered in this experiment, although more can be provided. The levels with the ranges of the six parameters selected are given in Table 4.2.

Table 4.2 The Levels with the Ranges for the Six Parameters Selected

<div>Level</div> <div>Parameter</div>	1	2	3	4	5	6
Frequency, f (Hz)	0.4	0.8	1.2	1.6	2.0	2.4
Amplitude, θ_l (deg)	6	8	10	12	14	16
Movable pin position, D	1	2	3	4		
Aspect ratio, r	8.71	6.82	4.80	3.21		
Spring at tail joint 3, k (N/mm)	0.98	2.45	4.61			
Water flow velocity, v (m/s)	0.034	0.102	0.171			

There will be 5184 runs if a full factorial design method is used. Hence, to reduce the cost and time in achieving the results, various strategies can be adopted for an appropriate choice of runs.

Depending on the characteristic and physical limitations of an experiment, there are various designs of experiments (DOE) available to provide the necessary data for sensible analysis to achieve the experimental objectives, while keeping

the number of runs in a manageable size. In this study, the Taguchi's orthogonal scheme [51] was employed. The orthogonal method of experimental design uses a special set of arrays called orthogonal arrays to construct an experimental plan.

By choosing the proper level of combinations of the various independent variables, these standard arrays stipulate the way of conducting a limited number of runs, but giving the full information of all the factors that affect the performance parameter. In this way, an extremely large number of test runs could be avoided. By using the orthogonal design method, the six parameters given in Table 4.2 resulted in 49 arrays or runs, as shown in Table 4.3.

The 49 runs of experiment generated by the orthogonal design were conducted in a water-tunnel system which will be discussed in the following section. Apart from the 49 runs, a further 60 tests were considered to provide sufficient “as measured” data for statistical analysis using the same experiment setup. Consequently, this experiment involved $49+60=109$ test runs, in total.

The detailed for the 109 of runs use in the experiment can be found in Appendix C-1.

Table 4.3 Orthogonal Arrays Generated for the Six Controlled Parameters.

Run No.	f (Hz)	θ_l (deg)	D	r	k (N/mm)	v (m/s)
1	1.2	16	2	8.71	4.61	0.0348
2	1.2	10	2	8.71	2.45	0.1708
3	2	16	1	4.8	4.61	0.0348
4	0.4	14	3	3.21	2.45	0.0348
5	1.6	6	2	3.21	2.45	0.0348
6	2.4	8	2	4.8	2.45	0.0348
7	2	12	3	8.71	2.45	0.0348
8	1.2	8	1	3.21	0.98	0.1028
9	2.4	6	4	8.71	0.98	0.0348
10	1.2	6	4	4.8	0.98	0.1028
11	0.4	16	1	8.71	2.45	0.1028
12	0.8	10	1	3.21	0.98	0.0348
13	1.6	6	1	4.8	2.45	0.1708
14	0.4	16	2	6.83	0.98	0.0348
15	0.4	14	1	8.71	4.61	0.1708
16	1.6	12	1	4.8	0.98	0.1028
17	0.8	6	1	8.71	2.45	0.1708
18	1.2	6	3	6.83	0.98	0.0348
19	0.4	6	1	8.71	0.98	0.0348
20	2.4	10	3	8.71	4.61	0.1028
21	2.4	6	1	6.83	2.45	0.0348
22	0.4	8	2	6.83	2.45	0.1028
23	2.4	14	2	4.8	0.98	0.1708
24	2.4	12	1	6.83	4.61	0.1028
25	2	10	2	4.8	0.98	0.1708
26	2	14	4	6.83	2.45	0.0348
27	0.4	10	3	4.8	2.45	0.1028
28	0.4	6	2	6.83	4.61	0.1028
29	0.4	12	2	4.8	0.98	0.0348
30	1.2	12	3	6.83	2.45	0.1708
31	0.4	8	4	8.71	0.98	0.1708
32	0.8	6	2	6.83	4.61	0.1708
33	0.8	14	3	6.83	0.98	0.1028
34	0.4	6	3	4.8	0.98	0.0348
35	0.4	12	4	3.21	4.61	0.1708
36	2	8	1	6.83	0.98	0.1708
37	2	6	2	3.21	4.61	0.1028
38	0.4	10	1	6.83	0.98	0.0348
39	1.2	14	1	4.8	4.61	0.0348
40	0.8	8	3	4.8	4.61	0.0348
41	0.4	6	3	4.8	4.61	0.1708
42	1.6	14	1	8.71	0.98	0.1028
43	1.6	8	3	8.71	4.61	0.0348
44	1.6	16	3	6.83	0.98	0.1708
45	2	6	3	8.71	0.98	0.1028
46	2.4	16	3	3.21	0.98	0.1708
47	1.6	10	4	6.83	4.61	0.0348
48	0.8	16	4	4.8	2.45	0.1028
49	0.8	12	2	8.71	0.98	0.0348

4.4.2 Nature of Force Measured

In order to evaluate the experimental results, a measurement of the force along the direction of the water flow was made. Equation (4.2) shows the summation of forces along the x-axis of the force transducer. The system net force ($F_{x-system}$) will be the force measured along the x-direction as recorded by the computer.

$$\begin{aligned}\sum F_x &= F_{x-system} \\ &= F_{tail} - F_{bd} \\ &= T_{tail} - F_{td} - F_{bd}\end{aligned}\tag{4.2}$$

First, at zero flow rates, the force sensor value was bias to zero. Thereafter, the water-tunnel's was set to run at the flow rates based on each run as indicated in Table 4.3. After the flow in the water tunnel become stable, the fish robot was turned on. Thus, the force captured by the force transducer will be the net thrust/drag force of the sweeping tail including the drag of the fish body as described in Equation (4.2).

The computer recorded the force generated in the 30 oscillation cycles after the first five cycles. Three measurements were taken for each test run and the average of the three was used as the data input for the Analysis of Variance (ANOVA) studies. Please refer to Appendix C-2 for the detailed experimental procedure.

4.4.3 Results and Analysis

(i) Analysis of Variance (ANOVA)

In order to identify the parameters that are significant in affecting the output thrust of the fish robot, an ANOVA has been carried out. First, we need to determine the trends of each individual parameter in order to carry out an appropriate ANOVA. Figures 4.5 (a-f) shows the trends of each individual

parameter plotted, using the data from the additional 60 runs of test as discussed in Section 4.4.1

Figure 4.5 Trends of the Six Controlled Parameters: (a) Frequency, (b) Amplitude, (c) Movable Pin Position, (d) Aspect Ratio, (e) Spring Constant, (f) Flow Velocity.

From Figures 4.5 (a-f), we can noticed that all the controlled parameters within the tested range/levels can be considered having a linear relationship with the output force generated. Hence, a simple general linear model Analysis of Variance (ANOVA) test can be used to determine how significant of each controlled parameter has on the output force.

The data collected from the 109 runs of test (as discussed in Section 4.4.1) were used as the data input to the statistic tools (Statistical Package for the Social Sciences, SPSS, [52]) and the result of the ANOVA is tabulated in Table 4.4.

First, we would like to find out how reliable the input data is, before interpreting the result from the ANOVA table. The “Adjusted R-Square” value shown in the bottom of Table 4.4 indicates the reliability of the input data and the significant test result.

Table 4.4 Analysis of Variance of the Six Controlled Parameters

Dependent Variable: Thrust

Source	F	Sig. <0.05
f	3.409	.053
θ_l	34.099	.000
D	1.427	.298
r	1.489	.282
k	1.675	.241
v	69.344	.000
$f * \theta_l$	.190	.959
$f * D$	8.062	.006
$f * r$	1.665	.241
$\theta_l * D$	.839	.506

R Squared = .998 (Adjusted R Squared = .976)

Statistically, with an ‘Adjusted R Squared’ value of 0.976, we can confidently interpret the result for the significances of each parameter.

It is straightforward to determine whether the parameters or their interactions have significant effects on the output thrust or not by reading the ‘Sig.’ column in Table 4.4. Those rows under the ‘Sig.’ column that have a value less than the selected significance level of 0.05 will be considered to have a significant effect on the output thrust. From Table 4.4, it shows that ‘ θ_l ’ and ‘ v ’ have significant effect on the output thrust, since have a value of 0.000 (<0.05). Besides, the interaction between the frequency and the movable pin position ($f*D$) also have a significant effect on the output thrust. Hence, with $f*D$ having significant effect on the output thrust, we cannot excludes factor f and d from further testing although they do not have significant effect on the output thrust.

The ANOVA also indicate that the water flow velocity (v) and amplitude (θ_l) that have an F value of 69.344, 33.099 respectively, have a more significant effect than the interaction between frequency and movable pin position ($f*D$).

It is noted that the SPSS software is not able to calculate the significant value for the several factor-interaction (not indicate in the table) due to insufficient runs of data. The 49 runs generated from the orthogonal design (discussed in Section 4.4.1) are only sufficient to calculate the significances for the main effect (f , θ_l , D , r , k , v). The additional 60 runs of test actually allow the software to solve for several second order interaction ($f*D$, $f*\theta_l$, etc.), but not all. However, this will not affect the result of the interpretation from the ANOVA table. But, by doing so, we assumed that the other 2nd and higher order interaction will not have significant effect on the output thrust except the interaction $f*D$ which were found to have significant effect on the output thrust.

According to the ANOVA results, the aspect ratio (r) and the spring constant (k) were found to have no significant effect on the output thrust. However, before we proceed to the detailed study on the significant parameters, we would like to take a closer look on how the aspect ratio and the spring constant influence the output thrust.

(ii) Detailed Study on the Effect of Aspect Ratio **Figure 4.6 Effect of the Aspect Ratio (r) on the Output Thrust.**

Basically, a higher fin's aspect ratio is more efficient than the lower aspect ratio because the fin would induce less drag per unit of lift or thrust produced [23, 53]. Note that the aspect ratio (r) is defined by H^2/A , where H is the vertical height between the two tip ends and A is the area of the fin surface.

It can be seen from Figures 4.6 (a & b) that a higher aspect ratio actually performed better as compared to the lower one. Nevertheless, one has to take note that for this experiment setup; the area of the smallest aspect ratio tail fin is made larger than that of the higher aspect ratio tail fin (refer to Figure 4.7). Thus, we would have expected more forces to be generated by a larger fin, but the results did not support that. Hence, we would say that a larger thrust force could be generated by using a higher aspect ratio tail fin, but not the one with small aspect ratio and larger tail fin area. Thus, in the future studies, the highest aspect ratio tail fin (8.71) will be used for better performance.

Figure 4.7 Type of Tail Fins Tested: Area A: 7711 mm², Aspect Ratio: 8.71; Area B: 9906 mm², Aspect Ratio: 6.82; Area C: 14096 mm², Aspect Ratio: 4.80; Area D: 21082 mm², Aspect Ratio: 3.21.

(iii) Detailed Study on the Effect of Spring Constant

The result in ANOVA discussed earlier shows that the spring constant does not have a significant effect on the output thrust generated by the oscillating fin. We have a hypothesis that this insignificance might be due to the inadequate range of spring constant used in the experiment. The range of the spring constant selected might be too narrow to show its effect on the output thrust. Hence, it was being analyzed to be an insignificant factor by the ANOVA as compared to the others. Thus, additional experiment had been conducted to study the effect of the spring constant (k) on the output thrust alone and to prove our hypothesis.

The additional experiment was carried out by constraining the spring joint (joint3 - refer to Figure 3.8), which can now be modeled as a rigid joint with very high spring constant value, in turn, making the range of the spring constant wider. The new results obtained were then plotted and compared with the other spring constants values obtained earlier. From Figure 4.8, it can be seen that the output thrust generated with a flexible joint (low spring constant of 0.98N/mm and 2.45 N/mm) is much higher than the one with a rigid joint (high spring constant) and the effect of the spring constant is more obvious when the

sweeping amplitude is larger than 10 degree. This increase in the net thrust force for a flexible tail joint is most likely due to the drag reduction on the tail fin. One can also noticed that the values of the thrust between spring constant of 0.98 N/mm and 2.45 N/mm are very close to one another. This result have supported our hypothesis that previous selected spring constant range for the ANOVA analysis was indeed too narrow to shows the significance of the spring effect. From this analysis, a flexible joint is preferred if a larger output thrust force is desired. This result also indicates a certain degree of drag reduction with this form of propulsion method by using a low spring constant.

Figure 4.8 Effect of Spring Constant on the Output Thrust with $v = 0.0348$ m/s and $r = 8.71$.

Thus, for the next experiment, we will focus on studying the effect of those parameters which have found to have significant effect on the output thrust with those insignificant parameter (r & k) kept at their optimal values (8.71 and 0.98 N/mm respectively). The parameters that we will focus are 1) frequency, 2) amplitude and 3) movable pin position.

Although the water flow velocity (v) has significant effect on the output thrust, it will not be included as a variable in future studies. This is because one would have expected the drag force of the fish robot to increase as the water flow velocity increases (refer to Figure 4.5 (f)). With an increase in drag, the net

thrust produced will decrease accordingly (refer to Equation (4.2)). Initially, this water-tunnel's flow velocity factor was included in the experiment with the intention of hoping to discover some interesting results rather than the expected one. Nevertheless, we will like to set the flow velocity to a constant value of 0.0348 m/s for the detail experiment on the significant controlled parameters. The inclusion of this flow is to provide a gentle constant free stream flow along the test section. This is to reduce the disturbance forces between the oscillating caudal fin and the water-tunnel sidewalls along the test section of the water-tunnel.

4.5 Experimental Study on the Significant Controlled Parameters

4.5.1 Design of Experiment (DOE)

A full factorial experiment will be conducted for the three parameters (frequency (f), amplitude (θ_l) and movable pin position (D)). The frequency (f) and amplitude (θ_l) were included in this study because they were found to have significant effect on the output thrust from previous ANOVA analysis. Although the main effect of movable pin position (D) have no significant effect on the output thrust, but its interaction with frequency ($f*D$) does, hence, it was also included in this study. The levels for frequency and amplitude used remained as six. However, the level for movable pin position (D) will be reduced to two, since the main effect of the movable pin position (D) was found to have no significant effect on the output thrust. We will keep the range of the three parameters the same as before, to check for the consistency of the ANOVA results. The three parameters and their respective level selected are tabulated in Table 4.5. There will be 72 runs ($6 \times 6 \times 2$) being considered in the experiment. The full factorial design arrays or runs are shown in Table 4.6.

Table 4.5 The Levels with the Ranges of the Three Parameters Selected (with k , v and r set at 0.98N/mm, 0.0348 m/s and 8.71 respectively)

Level Parameter	1	2	3	4	5	6
Frequency, f (Hz)	0.4	0.8	1.2	1.6	2.0	2.4
Amplitude, θ_1 (deg)	6	8	10	12	14	16
Movable pin position, D	1	4				

Table 4.6 Full Factorial Design of the Three Selected Parameters

Run	f	θ_1	D	Run	f	θ_1	D
1	1.2	6	1	37	2	6	1
2	2	16	1	38	0.8	6	1
3	0.8	16	4	39	0.8	8	4
4	2	10	1	40	1.6	12	4
5	0.4	16	4	41	2.4	6	1
6	2.4	8	1	42	1.2	14	1
7	2.4	12	1	43	2.4	14	4
8	2	14	4	44	1.6	16	4
9	0.4	6	4	45	1.2	10	4
10	1.2	12	4	46	0.8	10	4
11	2.4	12	4	47	1.2	8	4
12	2.4	16	1	48	0.8	10	1
13	1.6	12	1	49	2.4	8	4
14	0.4	14	4	50	1.2	14	4
15	0.4	14	1	51	0.4	16	1
16	2.4	6	4	52	1.6	10	1
17	0.8	16	1	53	2	8	4
18	2.4	10	1	54	0.4	8	1
19	1.6	8	4	55	0.8	12	1
20	0.4	10	4	56	0.8	12	4
21	2.4	14	1	57	1.6	16	1
22	1.6	6	1	58	0.4	10	1
23	2	12	4	59	0.4	12	1
24	1.6	8	1	60	1.6	14	4
25	0.4	12	4	61	1.2	16	4
26	0.8	8	1	62	2	8	1
27	1.2	8	1	63	1.6	14	1
28	1.2	12	1	64	2	16	4
29	2	10	4	65	2	12	1
30	2	6	4	66	0.4	8	4
31	2.4	10	4	67	2	14	1
32	1.6	6	4	68	0.4	6	1
33	1.2	6	4	69	1.2	16	1
34	1.6	10	4	70	0.8	14	4
35	2.4	16	4	71	1.2	10	1
36	0.8	14	1	72	0.8	6	4

4.5.2 Nature of Force Measured

The nature of force measured is similar to that discussed in Section 4.4.2. Please refer to Appendix C-3 for the detailed experimental procedure.

4.5.3 Results and Analysis

(i) Analysis of Variance (ANOVA)

From the ANOVA table (Table 4.7) one can notice that the main effect of frequency (f) and amplitude (θ_l) have significant effect on the output thrust of the oscillating fin, since their respective 'Sig.' values is less than 0.05. The main effect of movable pin position (D) is not significant based on the analysis, but its interaction with the frequency ($f*D$) is. In addition, the interaction of $f*\theta_l$ was also found to have significant effect on the output thrust. This result tally well with the previous studies (refer to Section 4.3) and is considered to be more reliable because it is a full factorial design and have a higher adjusted R square value.

Table 4.7 Analysis of Variance of the Three Most Significant Factors (f , θ_l , D)

Dependent Variable: Thrust

Source	F	Sig. < 0.05
f	155.507	.000
θ_l	431.641	.000
D	.739	.398
$f * \theta_l$	13.549	.000
$f * D$	12.191	.000
$\theta_l * D$	.661	.656

R Squared = .993 (Adjusted R Squared = .979)

The rank of significance for the various factors and interaction are as follow: 1) Amplitude, θ_l (F =431.641), 2) Frequency, f (F=155.507), 3) Interaction of frequency and amplitude, $f*\theta_l$ (F=13.549), and lastly the interaction of frequency and movable pin position, $f*D$ (F=12.191). From the 'F' value in

Table 4.7, one can noticed that the amplitude (θ_l) greatly influence the output thrust as compared to the frequency and the interaction of $f*\theta_l$ and $f*D$.

In the following section, we will be analyzing in detail on how this main effect and interaction affect the trend of the output thrust generated.

(ii) Effect of Frequency (f) on the Output Thrust

Figure 4.9 Effect of Frequency (f) on the Output Thrust with $k = 0.98$ N/mm, $\nu = 0.0348$ m/s and $r = 8.71$.

Figure 4.9 (a) and 4.9 (b) shows the effect of frequency on the output thrust at movable pin position '1' (D1) and '4' (D4) respectively. It can be noticed that the output thrust increases as the frequency increases and it peaks at a frequency of around 1.6 to 2 Hz for most of the runs. Thereafter, the output thrust decreases with a further increase in frequency. The peak at the range of 1.6 to 2 Hz was first thought to have caused by the speed limitation of the motor when operating at a high frequency, but the encoder signal shows that it is not the case. Another possibility of the peak in output thrust at that range might be due to the natural frequency of the system. Nevertheless, further dynamic modeling and testing have to be carried out in order to support this assumption. One can also notice that with higher amplitude of oscillation, the resultant output thrust will be also increased. However, regardless to the amplitude, the peak of the output thrust still occur at around 1.6 to 2 Hz frequencies.

(iii) Effect of Amplitude on Output Thrust

Figure 4.10 Effect of Amplitude (θ_1) on Output Thrust with $k = 0.98$ N/mm, $\nu = 0.0348$ m/s and $r = 8.71$.

Figures 4.10 (a-d) show the effect of the amplitude (θ_1) on the output thrust. Learning from previous experiments done by [9, 54], one would have expected to see an increasing trend up to a peak point and then followed by a decreasing trend. The increasing trends are shown very clearly in Figure 4.10 (a-d), but not for the peak and decreasing trend.

The range/level of the amplitude (θ_1) selected for the experiment may not be enough to show the expected trend. Hence, a few additional test runs were added with the aim to observe the trends. Two more levels (18 and 20 degree) of the amplitude were added to the design. Additional runs of experiment were carried out, but only the runs with frequency of 1.2 Hz and below were recorded due to the experiment limitation, thus, there will be an additional of 12 experimental runs. Figures 4.11 (a) and (b) show the new results plotted.

Figure 4.11 Effect of Amplitude (θ_I) on Output Thrust with $k = 0.98$ N/mm, $v = 0.0348$ m/s and $r = 8.71$.

The trends of the expected increasing and decreasing slope were noticed in Figure 4.11 (a). It was found that the oscillating amplitude peak is at a value of 18 degree for all the three frequencies (0.4 Hz, 0.8 Hz and 1.2 Hz). As for Figure 4.11 (b), although the decreasing trends was not noticed in this graph, but by studying the trend of the three slopes, the peak can be expected to be around 20 to 22 degrees.

Due to the mechanical linkages of the tail fin design, it may not be adequate to just looked at the effect of the amplitude (θ_I) on the output thrust, since the tail end position (i, refer to Figure 3.9) is depend not only on the amplitude (θ_I) alone, but also the movable pin position (D). Hence, in order to have a clearer understanding on why the peak occurred at these ranges, we will like to look at the effect of the sweeping amplitude (Q , refer to Figure 3.9 b) on the output thrust. As studies have shown that, the (double) sweeping amplitude to fish length ratio for all species of fish was in a range of 0.20 to 0.24. For high propulsion efficiency, the sweeping amplitude of the fish should be around 10 to 12 percent of its body length [12]. Hence, we would like to determine whether the peak we observed earlier lies within this range.

Noted that the sweeping amplitude was chosen to be ' Q ' instead of ' R ', this is because of the difficulties in obtaining the actual sweeping amplitude ' R '.

Therefore, the value of ' Q ' was taken to be the estimated sweeping amplitude with the assumption that the value of ' Q ' and ' R ' will be quite close, due to the small spring constant value (0.98 N/mm) used in the experiment.

The value of the sweeping amplitude (Q) for each corresponding amplitude (θ_l) and movable pin position (D) can be found by using Equation (3.3). The values of sweeping amplitude (Q) and the percentage ratio of it to the fish's length were tabulated as shown in Table 4.8.

Table 4.8 Value of Sweeping Amplitude (Q) and Percentage of Sweeping Amplitude to Fish's Length Ratio for each corresponding value of Amplitude (θ_l).

Amplitude θ_l, degree	Sweeping Amplitude Q, mm ($D1$)	Percentage of Q to Fish's Length Ratio, %	Sweeping Amplitude Q, mm ($D4$)	Percentage of Q to Fish's Length Ratio, %
6	34.9	5.28	22.43	3.39
8	44.62	6.75	29.63	4.48
10	53.18	8.05	36.61	5.54
12	60.65	9.18	43.34	6.56
14	67.15	10.16	49.78	7.53
16	72.83	11.02	55.92	8.46
18	77.83	11.77	61.75	9.34
20	82.27	12.45	67.26	10.18
22	86.24	13.05	72.47	10.96
24	89.83	13.59	77.36	11.7

With the values found in Table 4.8, the output thrust against the percentage of sweeping amplitude to fish's length ratio were plotted and were shown in Figures 4.12 (a & b).

From Figure 4.12 (a), it can be seen that the peak indeed occurs in the range (10 to 12 %) observed by other researcher. As for Figure 4.12 (b), although the decreasing trends were not fully observed, but from the slopes of the trend, it seems highly that the peak would lie in the optimal range of 10 to 12 percents. Hence, it can be concluded that to obtain a maximum thrust force, the sweeping amplitude (Q) should be kept within the range of 10 to 12 percent of the fish's body length.

(a)

(b)

Figure 4.12 Effect of the Percentage of Sweeping Amplitude to Fish's Length Ratio on the Output Thrust – (a) at Movable Pin Position D1 (b) at Movable Pin Position D4. With $k = 0.98$ N/mm, $v = 0.0348$ m/s and $r = 8.71$.

(iv) Effect of Interaction between the Frequency and Amplitude on the Output Thrust

From the result of the ANOVA test, it is shown that the interaction between the frequency and amplitude has a significant effect on the output thrust. This interaction can be explained from the input motion given to the motor that drives the tail fin. For all the run, the programmed input motion is a sine wave (refer to Equation (3.7)). Thus, the output motion of the oscillating fin will be a sine-wave profile as shown in Equation (4.3).

$$Y(t) = \theta_1 \sin \omega t \quad (4.3)$$

In addition, its velocity profile will be:

$$\begin{aligned}\dot{Y}(t) &= \theta_1 \omega \cos(\omega t) \\ &= 2\pi f \theta_1 \cos(2\pi f t)\end{aligned}\quad (4.4)$$

From Equation (4.4), one can notice the relationship of frequency and amplitude had on the output velocity of the oscillating fin. Thus, for a given a constant oscillating velocity, we can play with the magnitude of the frequency and amplitude.

A bar chart of the runs with the same sweeping velocity (product of $f*\theta_1$ is a constant) is shown in Figure 4.13. Note that each interval on the x-axis ($f*\theta_1$) represents a set of constant velocity of the oscillating tail fin, but not the actual value of the velocity itself or the velocity of the fish robot.

By virtue of Figure 4.13, one can observe how the frequency and amplitude affect the output thrust generated under a constant oscillating velocity. It can be seen that the trend are the same for all the oscillating velocity. Under a constant oscillating velocity, the run with a lower frequency and higher amplitude always generates a larger thrust as compared to the one with higher frequency and lower amplitude.

Figure 4.13 Effect of Interaction ($f*\theta_1$) on the Output Thrust with $k = 0.98$ N/mm, $v = 0.0348$ m/s and $r = 8.71$.

This result implied that, if we required a higher thrust (normally during accelerating or moving from rest), it will be better to operate the tail fin at a lower frequency and a high amplitude. Once it reached a constant speed, a low-amplitude and high-frequency setting is preferred. This phenomenon on the effect the $f*\theta_I$ interaction will be clearer after the relationship of thrust and swimming speed of the fish robot have been discussed.

(v) Effect of Interaction between the Frequency and the Movable Pin Position on the Output Thrust

Figures 4.14 (a-d) show the effects of the interaction between the frequency and the movable pin position on the output thrust of the oscillating fin. Note that joint '2' angle (θ_2) at 'D1' is larger than that of 'D4' under the same oscillating amplitude (θ_I). Please refer to the motion studies section for definition of the joint angles and their relationship.

Figure 4.14 Effect of Movable Pin Position (D) on Output Thrust with $k = 0.98$ N/mm, $\nu = 0.0348$ m/s and $r = 8.71$.

One would have expected a bigger sweeping angle to generate a larger output thrust as the frequency of oscillating fin increases, but from the above figures, it is not the case.

From Figures 4.14 (a-d), we can noticed that there is an interaction between the movable pin position (D) and the frequency of oscillation (f). This results supported the ANOVA test earlier, which indicated a significant value for the interaction of frequency and movable pin position ($f*D$). It is noticed that movable pin position ' $D1$ ' generates larger output thrust as compared to ' $D4$ ' when operated at a frequency of 1.6 Hz and below. When the operating frequency is above 1.6 Hz, movable pin position ' $D4$ ' will be more preferred since it generates a higher output thrust.

One has to take note that by changing the position of the movable pin from ' $D1$ ' to ' $D4$ ' will result in a decrease in sweeping amplitude (Q). Hence, this study was somehow related to the previous one (the effect of the interaction between the frequency and amplitude). By referring to Figures 4.14 (a-d) again, it can be noticed that at higher frequency the output thrust generated at ' $D4$ ' is indeed larger then that of ' $D1$ '. It can be conclude that smaller sweeping amplitude (Q) is desired if the fish robot is operating at a higher frequency.

Also noted that, for this current tail fin design, the movable pin position (D) cannot be adjusted during operation. Hence, the joint 2 angle (θ_2) is fixed during operation and there is no phase difference between joint 1 and joint 2. If there is a need to study the effect of phase difference between the two joints, we may need to re-design or modify the existing tail fin mechanism to make the movable pin adjustable during operation.

4.6 Experimental Study on the Relationship between the Thrust and the Fish Velocity (Fixed Body Motion)

It is important to find out the relationship between the output thrust and the swimming velocity of the fish robot, as it is the key of this research. This information would enable us to tune the various parameters to the desired output thrust, which in turn allows us to control the speed of the fish robot.

With this swimming velocity (Fixed Body Motion) known for a given set of parameters, we can then compare it with the respective self-propelled velocity (Free Body Motion) found from the experiment in the water tank, that would be discussed in Section 4.8. A potential drag reduction can then be demonstrated if the self-propelled speed is greater than the one conducted in the water-tunnel laboratory with the front body of NAF-I fixed.

Before these studies, our hypothesis is that a greater thrust will generally produce a faster swimming speed. With this experiment, we hope to test out our hypothesis and to find out its actual relationship, in order to carry out more specific analysis and conclusion.

4.6.1 Nature of Force Measured

In this experiment, an indirect method is used to measure the speed of the fish robot for a given run. It requires the reading from the force sensor and tuning of the water-tunnel's flow velocity. Only 32 runs (for movable pin position, DI) out of the 72 runs listed in Table 4.6 will be considered in this experiment, since, the movable pin position (D) is not an independent variable and will only contribute to an overall increase in sweeping amplitude (Q). The details of the experiment procedure are as followed.

Firstly, the net thrust force of the oscillating fin for all the runs are being recorded using the force transducer. The measuring of the net thrust force is

obtained under zero water-tunnel flow, which means that there is no flow in the water-tunnel system during the time when the force is being captured. The net thrust force is obtained by summation of the thrust produced by the tail and drag induced by the fin motion as shown in Equation (4.5).

$$F_x = F_{tail} = T_{tail} - F_{td} \quad (4.5)$$

After the net thrust forces for each given run was obtained, the next step is to determine the speed of the fish robot for each run. The fish robot was set to oscillate based on the parameter setting for each particular run. Thereafter, the speed of the fish robot was obtained by tuning the water-tunnel flow velocity until the resultant force in the x-direction is zero. The water flow over the fish robot will cause an additional drag (drag force due to the fish body, F_{bd}). Thus, the summation of force components in the x-direction is the same as Equation (4.2).

After the setting the parameters for each run, the force sensor value was bias to zero. Thereafter, the fish robot was set to oscillate. At zero water-tunnel flow velocity, the force measured by the force transducer for that particular run should be corresponded to that previously recorded (F_{tail} at zero flow velocity). Next, we will start the flow in water-tunnel and slowly increase it until the force transducer's reading along the x-axis is equal to zero. At this moment, it means that the total thrust force produced by the oscillating fin is equal to the total drag force of the fish robot at that particular water-tunnel's flow velocity ($\sum F_x = 0$).

From Equation (4.2),

$$\sum F_x = F_{x-system} = T_{tail} - F_{td} - F_{bd}$$

at $\sum F_x = 0$, implies

$$T_{tail} - F_{td} - F_{bd} = 0$$

$$T_{tail} = F_{td} + F_{bd} \quad (4.6)$$

The water-tunnel's flow velocity at this instant will be equal to the speed of the fish robot for that particular run. Please refer to Appendix C-4 for the detailed experimental procedure.

4.6.2 Result and Analysis

Figure 4.15 Relationship between the Net Tail Force (F_{tail}) and the Swimming Velocity of the Fish Robot (Fixed Body Motion) with $k = 0.98$ N/mm and $r = 8.71$.

Figure 4.15 shows the swimming velocity of the fish robot (v_{fix}) plotted against the net thrust force (F_{tail}) generated by the oscillating tail for various frequencies. One can observe that the swimming velocity increase linearly as the net thrust force increases for all set of oscillating frequency. However, the swimming velocity is not directly related to the net thrust force. For a same net thrust force produced, the one with a higher oscillating frequency will be able to attain a higher constant swimming velocity as compared to the one with a lower frequency. This is true only if, the amount of net thrust force generated is

enough to accelerate the fish robot or overcome its inertial to reach that velocity. Thus, we may still need the lower- frequency and high-amplitude setting to generate enough thrust for the fish robot to move from rest or to overcome it inertial. After it gained its momentum, we can then switch to a setting with higher-frequency and low-amplitude to cruise at the desired speed. This relationship can be useful for future motion control of the fish robot, where the fish robot will be programmed to swim in a more effective way.

With the swimming speed of various run obtained, the range of Strouhal number (St) in which the fish robot performed in can be determined. The Strouhal number is a dimensionless parameter that can be used to describe the tail or wing kinematics of swimming or flying animals. It is defined as $St = \frac{fA}{U}$, where f is the tail oscillating frequency (Hz), A is the wake width (found experimentally) and U is the average forward velocity (equal to the swimming velocity found in earlier). This dimensionless numbers are important in biomechanics because their condition of being constant can imply dynamic similarity between systems, even if there are possible differences in size or medium.

Triantafyllou et al. [12] concluded in his studies that, in oscillating foil, thrust development is optimal for a specific range of St (namely $0.2 < St < 0.4$). Existing data from a number of fish species also revealed that their St values lie in this predicted range. Studied done by Rohr and Fish [55] on larger variety of cetaceans have showed that most cetaceans indeed swim at Strouhal values between 0.2 and 0.4, with a preferring a range of 0.2-0.3 where maximum efficiency occurs. Thus, it is crucial to determine the St for our fish robot in order to compare it with the existing results by other researchers. From the analysis of the comparison, we hope to find out how our fish robot preformed as compared to the nature and what are the areas (with focused on mechanical design) which can be improved to further enhance its performance.

The Strouhal values (St) of the fish robot for the various run were calculated and plotted as shown in Figure 4.16. From the chart, most of the St values lie in the range between 0.8 and 1.1, which does not tally with the optimal values found by others [12, 55]. Based on how the Strouhal number is defined ($St = \frac{fA}{U}$), the high St values obtained in our experiment were mainly caused by the low forward swimming velocity measured, due to the high body drag of the fish robot, especially at high frequency. One of the major difference between our setup and that of Triantafyllou and Rohr [12, 55] is that their test specimens have a streamline body (hydro foil and real fishes respectively), but ours have a large buff body in front of the oscillating tail fin which may had significantly increase the drag force component.

If the body drag of the fish robot is negligible (assumed to have a streamline body), the thrust force (T_{tail}) need only to overcome the drag created by the oscillating tail (refer to Equation (4.2)). This in turn, would increase the overall swimming velocity (with the assumption that the relationship between the net thrust force and the water flow is linear).

Figure 4.16 Strouhal Number for NAF-I

The Strouhal values of the runs based on the above assumption were estimated and plotted as shown in Figure 4.17. The estimated Strouhal values based on the assumption lie in the range between 0.52 and 0.72, which is still not in the range of 0.2 to 0.4 found by other [12, 55]. This may be caused by the higher drag on the oscillating tail, due to the flow disturbance caused by the fish body. Although the body drag has been neglected, but we did not account for the disturbance in flow caused by the fish body (act as a bluff body). Thus, the drag generated by the oscillating fin could be higher. For present studies, it is not possible to quantify how significant the disturbances had on the drag of the tail fin. More experiments have to be carried out, in order to support the assumption made earlier regarding the high body drag.

Figure 4.17 Estimated Strouhal Number for NAF-I with Streamline Body.

4.6.3 High Body Drag Assumption Verification by Computation Fluid Dynamic (CFD) Analysis

To support the assumption made earlier regarding the high body drag, a computation fluid dynamic (CFD) simulation was conducted on the original cad model and a modified cad model (more streamline body) of the fish robot. Drag force will be obtained for comparison. Investigation will also be conducted to find out how different body structure affects drag force.

Figure 4.18 Body Drag Force, F_{bd} Comparison Between the Experimental Result and the CFD Simulation Results (Original and Modified Cad Model of the Fish Robot's Body).

We can see from Figure 4.18 that drag force for modified body structure are lower than that for the original body structure. Simulations were also conducted for five different velocities. The impact of the modified body structure is felt most at a higher water-tunnel flow velocity with the biggest reduction in drag force. We can conclude that body structure definitely affects the drag force but we would like to know in more detail on how the decreasing in drag force is being achieved. We shall use the graphical results gathered from the simulation to aid us in our investigation.

Figure 4.19 CFD Simulation Result on the Original Cad Model of the Fish Robot's Body.

Figure 4.20 CFD Simulation Result on the Modified Cad Model (More Streamline) of the Fish Robot's Body.

Fluid flow path-line for original and modified body structure are shown in Figure 4.19 and Figure 4.20 respectively. From Figure 4.19, we can see that fluid flow is disrupted when it flow past original body structure. Large vortices and velocity gradient can be seen at the back of the fish robot's body. As compared to original body structure, modified body structure (as shown in Figure 4.20) has little flow disruption, no vortices and small velocity gradient.

As we know that drag component consists of viscous drag, pressure drags and induced drag. Friction drag is caused by viscosity of water in flows with large velocity gradients, distortion of flow around fish causes pressure drag and lastly, the induce drag is caused by energy lost in the vortices [23]. Thus, we can deduce that the body structure affects the formation of vortices, velocity gradient and cause disruptions in fluid flow which in return affect the drag force.

From the above study, we can conclude that the current fish robot's body has induced a high body drag due to its non-streamline body. Results from the CFD simulations have shown that a more streamline fish's body will significantly reduced the body drag especially at high flow velocity. Hence, if the fish robot has a streamline body, it will be able to operate in the desire Strouhal range of 0.2 to 0.4 where maximum efficiency occurs.

4.7 Experimental Study on the Relationship between the Thrust and the Fish Velocity (Free Body Motion)

With the relationship between the swimming speed and the thrust found in Section 4.6, we can now carry out the study on a self-propelled fish-like underwater (free body motion). In the previous experiment (section 4.6), the fish robot body is being held rigid by the connecting rod in order to measure the thrust force being produced. In this experiment, we allow the fish robot to swim freely in the water tank. This allows its body to yaw freely under the influences of the caudal tail fin motion. Thus, this experiment was conducted with the aim to demonstrate a potential drag reduction of self-propelled fish robot (free body motion) as compared to fixed body swimming speed (conducted in water-tunnel). In addition, quantitative results will be collected for determining the coefficient of the swimming speed prediction model, which will be discussed in Chapter 5.

4.7.1 Experimental Setup and Procedure

This experiment was conducted in a water tank in the Robotic Research Centre (RRC), as shown in Figure 4.21.

Figure 4.21 Experimental Setup at Robotic Research Center Water Tank.

In this experiment, the time for the fish robot to travel through a predefined distance (1 meter) is being measured using a timer, where the start and stop of the timer is being activated through a pair of infra sensor as shown in Figure 4.21. In addition to the timer, a stopwatch was also used to record the travel time for each run concurrently. This is to ensure the consistency of the time being recorded. The same 32 runs as mentioned in Section 4.6 will be considered in this experiment. For each run, three measurements will be taken and the average of the three measured data will be used as the input for analysis. The detailed experimental procedures are as follow:

1. The fish robot is being placed at the starting position as shown in Figure 4.21
2. The parameters for that particular run are being set.
3. The fish robot is remotely started and swim for a distance of about 1.2m before the timer and stopwatch are activated.
4. Three measurements will be taken for each run and the average of the three data is recorded.
5. The experiment is then repeated for the other runs.

4.7.2 Result and Analysis

Figure 4.22 Relationship between the Net Tail Force (F_{tail}) and the Self-Propelled Swimming Velocity of the Fish Robot (Free Body Motion) with $k = 0.98$ N/mm and $r = 8.71$.

Figure 4.22 shows the swimming velocity of the fish robot with free body motion plotted against the net thrust force (F_{tail}) generated by the oscillating tail for various frequencies. One can observe that the trends were identical to those discussed in Section 4.6.2. Swimming velocity increases as the net thrust force increases for all sets of oscillating frequency. By comparing Figure 4.15 and Figure 4.22, the potential drag reduction in free body swimming motion were only observed for cases where the oscillating frequency is above 1.6 Hz.

In chapter 5, we will be using the output thrust data measured under ‘Fixed Body Motion’ to establish the thrust prediction mode, thereafter, the swimming velocity prediction model will be built based on it. Thus, the resulting swimming velocity model will predict the swimming velocity of the fish robot under ‘Fixed Body Motion’. However, under actual application of the fish robot (for example: autonomous navigation), a swimming velocity prediction model for a ‘Free Body Motion’ will be more appropriate, since the fish robot’s body will be free to yaw during operation. Hence, there is a need to determine the relationship between the ‘Fixed Body Motion’ and ‘Free Body Motion’ swimming velocity of the fish robot in order to tune the speed prediction model (Section 5.4) accordingly.

Figures 4.23 (a-f) shows the effect of the fixed and free body motion had on the swimming velocity of the fish robot. One can notice that the swimming velocity of the fish robot was found to be higher for the ‘Fixed Body Motion’ as compared to the ‘Free Body Motion’ when the oscillating frequency is less than 1.6 Hz. However, once the oscillating frequency is above 1.6 Hz, the ‘Free Body Motion’ cases will result in a higher swimming velocity as compared to the ‘Fixed Body Motion’ under the same parameters setting. Through visual observation during the experiment testing, the increases in swimming velocity were mainly due to the reduction in yawing motion of the fish’s body. These side forces (yawing motion) do not contribute to the forward velocity and was regarded as unwanted energy being wasted. This result shows that the body motion of the fish robot and the oscillating frequency have influences on its

overall swimming velocity. Hence, a certain degree of flexibility is essential to reduce the yawing effect of the fish robot's body especially under lower oscillating frequency. However, in this thesis, we will carry on with the formulation of the speed prediction model using the existing fish robot.

Figure 4.23 Effect of Fixed & Free Body Motion on the Swimming Velocity of Fish Robot with $k = 0.98$ N/mm and $r = 8.71$.

In real-life application, we will be more interested in the 'Free Body Motion' rather than the 'Fixed Body Motion', since it resembles the nature swimming motion of the fish. Hence, we need to introduce a coefficient to form the relationship between the swimming velocity of 'Fixed Body Motion', v_{fix} and the swimming velocity of 'Free Body Motion', v_{free} , where we define as follows:

$$v_{free} = \beta v_{fix} \quad (4.7)$$

where β is the correction factor being introduced.

With this relationship formed, we can now look at how the correction factor, β is being influenced by the input parameters (frequency, f and amplitude, θ_1).

By manipulating the Equation (4.7), we have:

$$\beta = \frac{v_{free}}{v_{fix}} \quad (4.8)$$

We utilize the experimental results from Section 4.6.1 and 4.7.1 to determine the values of the correction factor, β for various runs and plotted on the chart as shown in Figure 4.24. As we can see, the correction factor, β is not a constant for all the cases. It is depending on the input parameters, f and θ_1 . Hence, we can conclude that

$$\beta = \Psi(f, \theta_1) \quad (4.9)$$

Figure 4.24 Effect of Frequency (f) and Amplitude (θ_1) on the Correction Factor (β).

It is also notice that as the amplitude increases, the correction factor decreases for all cases of frequency. By referring to Equation (4.7), a decreasing in β will mean that the measured ‘Free Body Motion’ swimming velocity is less than what has been found in the ‘Fixed Body Motion’ experiment. Through visual observation during the experiment testing, the decrease in swimming velocity was mainly due to the larger amount of side forces generated when the amplitude increases. These side forces do not contribute to the forward velocity and was regarded as energy being wasted. These may explain why the fish are usually observed to swim with small amplitude and high frequency [12].

In Chapter 5, we will discuss the curve fitting method being used to predict the correction factor, β for all the runs based on Equation (4.8) and the experimental results found earlier.

4.8 Field Testing

Figure 4.25 Fully Assembled Fish Robot Submerged in Nanyang Lake.

The fish robot was brought to the “Nanyang Lake” for a field test (shown in Figure 4.25) to verify the potential drag reduction at a high oscillating frequency found in Section 4.7.

During the field test, the frequency, amplitude, movable pin position, aspect ratio and spring constant were set to 0.8 Hz, 8°, 1, 8.71 and 0.98 N/mm,

respectively. The fish robot is allowed to swim freely in along the pond for a distance of 10 meters. A stopwatch is used record the time taken for the NAF-I to covered the length. The same set of parameters was repeated three times for each upstream and downstream to obtain the average swimming speed for that run. The purpose of doing an upstream and downstream test is to filter off any external disturbance due to the water flow. The whole process of the experiment is being recorded using a video camera, thus the average velocity of the fish robot can be further confirmed through the video recorded.

The result of the field test was encouraging. The fish robot was able to achieve an average speed of 19.8 meters per minute (equivalent to half a body length per second, 0.5 BL/s), which is significant higher than the experimental speed (0.2BL/s, under the same parameters setting, refer to Section 4.6) found from the water-tunnel experiment. The swimming speed of NAF-I is also significantly greater than the NAW-I (earlier version: maximum swimming speed of 0.08 BL/s at laboratory condition) by a factor of six.

The field test has shown a potential drag reduction in a self-propelled fish-like underwater (NAF-I) and the result is consistent with the respective 'Free Body Motion' experimental result found in Section 4.7.

4.9 Summary

Parametric experimental studies on the fish-like underwater vehicle were conducted in the water-tunnel system to determine the effect of the various parameters had on the output thrust generated by the oscillating fin. The result from the statistic test had shown that the parameter frequency (f) and amplitude (θ_1) have significant effect on the output thrust. Although the spring constant was not found to have significant effect on the output thrust, but a further experiment testing have shown that the inadequate range of spring constant used in the studies may had caused its in-significance. The experimental studies

on the effect of the flexible passive spring joint have shown the signs on drag reduction.

From the parametric study and experiment analysis, we have found that in order to produce a larger thrust force, the selection of the parameters plays a very important part. From the studies, a combination of a relatively high frequency (2.0 Hz), a sweeping amplitude (Q) to fish's length ratio of about 0.1-0.12, a high aspect ratio (8.71), a movable pin position at ' $D4$ ' and a softer spring (0.98 N/mm) can produce the largest thrust force.

The results from the 'Fixed Body Motion' and 'Free Body Motion' swimming velocity comparison have shown that the body motion of the fish robot and the oscillating frequency have influences on its overall swimming velocity. The sign of potential drag reduction is more obvious when the oscillating frequency is above 1.6Hz where the fish's body yawing motion is smaller as compared to the lower oscillating frequency. Hence, a certain degree of flexibility is essential to reduce the yawing effect of the fish robot's body especially under lower oscillating frequency.

During the field test, the NAF-I was able to achieve an average speed of 19.8 meters per minute (equivalent to half a body length per second, 0.5 BL/s).

CHAPTER 5: SEMI-EMPIRICAL MODELING

5.1 Introduction

In the previous chapter, the effects of the various parameters on the output thrust generated and the swimming velocity of the fish robot have been analyzed. This analysis had provided a guideline for the selection of various parameters. However, in order to effectively control and optimize the output thrust and swimming speed of the fish robot on a mathematical and quantitative basis, it is essential to develop predictive models for the thrust generation and swimming velocity of the fish robot. The model formulated is believed to be useful in future navigation control of the fish robot. This model can also be used as a guideline for others to develop their fish robot's mechanism based on the predictive thrust and swimming speed required.

Generally, there are three approaches to model the forces: theoretical, empirical and semi-empirical. A theoretical model has a high accuracy and provides precise prediction, but the development of theoretical model needs a fundamental understanding of a process or mechanism, and usually leads to a very complicated form that is difficult to be used directly in practice. Furthermore, many important engineering problems cannot be solved completely by theoretical method, particularly in underwater environment where many phenomena such as vortex generation and flow dynamic have not been fully understood. Another method of attacking the problem is the use of empirical model where no mathematical equation is required. However, the empirical method is difficult to organize and correlate the results to obtain useful relationship for practical applications. In this work, a semi-empirical model will be developed based on some basic fundamental theories and experimental results. A dimensional analysis method, a method between mathematical development and a completely empirical study, is one of the powerful tools to develop semi-empirical models for engineering problems.

In this chapter, predictive models will be developed for the output thrust generated and the swimming velocity of the fish robot. The modeling will start with the construction of predictive output thrust model before progressing to construction of the model for swimming velocity prediction. A dimensional analysis approach will be used to find the mathematical relationships between the output thrust generated and the swimming velocity of the fish robot with respect to the various influencing parameters. Finally, the plausibility and predictive capability of the models will be assessed both qualitatively and quantitatively by analyzing the trends of the predictive models and by comparing with the experimental results.

5.2 Thrust Generation of Fish

Thrust forces are generated as fish moves its body and fins relative to water by displacing the water. As fish swims, it generated thrust by transferring the momentum to the surrounding fluid [23]. Since water is an incompressible fluid, any action force will produce an equal and opposite force [56]. Most of the fish's motion comes from the vortices shedding at its caudal fin and it was believed that the fish utilize these vortices to achieve very efficient swimming [57].

The wake left behind the tail of an undulatory swimmer is an array of trailing discrete vortices of alternating sign, generated as the caudal fin moves up and down (see Figure 5.1 (a)). Vortices in the wake have a reversed rotational direction as compared to the well-documented von Kármán vortex street, which is observed in the wake of stationary objects such as cylinders or aero foils (see Figure 5.1 (b))[12].

Figure 5.1 (a) The wake of a swimming fish has reverse rotational direction, associated with thrust generation. (b) The von Kármán vortex street generates a drag force for bluff bodies, placed in a free stream[12].

Although the generation mechanism of this wake structure is still unclear, the observed phenomenon, named reverse von Kármán vortex street, appears to be closely associated with thrust generation.

According to the research done by Muller et al. [58], the oscillation of the fish tail creates a circulating flow around the inflection points of the body, as shown in Figure 5.2. The circulating flow propagates along the body, and upon reaching the caudal fin, it interacts with the bound vortices created by the tail movements, forming the discrete vortices. This is so-called “undulating pump” mechanism.

Figure 5.2 The flow field around the body of a carangiform swimmer, as obtained from PIV data. The symbols P and S corresponding to pressure and suction zones that form the basis of the undulating pump mechanism[58].

In our experiments, the visual results agreed with the “undulating pump” mechanism. As shown in Figures 5.3 (a-b), the vortex behind the tail rotated clockwise and counter-clockwise as the fin is sweeping upwards and downwards respectively. The rotating direction of the vortex generated by the oscillating caudal fin is the same as that in the literature. It is believed that the

oscillation of the caudal tail fin causes a pressure difference between the sides of the tail fin [12, 15]. This pressure differences and the vortices generated during the oscillating motion were believed to be strongly related to the thrust generation. Hence, in later section, we will formulate our thrust prediction model based on this relationship.

(a)

(b)

Figure 5.3 Vortices Generated by Caudal Fin Oscillation: (a) Fin Moving Upwards; (b) Fin Moving Downwards.

For a fish swimming at a constant speed, its thrust must be sufficient to overcome its drag. Hence, our prediction model for the swimming velocity of the fish robot will be based on the convention drag force equation [12, 59, 60] as shown in Equation (5.1).

$$F_d = \frac{1}{2} \rho C_d A_c v^2 \quad (5.1)$$

where

F_d is the drag force, which is defined to be the force component in the direction of the flow velocity

ρ is the density of the fluid

C_d is the drag coefficient

v is speed of the fish robot relative to the fluid

A_c is the reference area, which is defined to be the maximum frontal area of the fish robot during motion (For example, the maximum cross-section area when viewed from the ahead).

The drag coefficient value used in this study will be based on steady-state estimation from the experimental data, due to the absence of information on the value of unsteady drag coefficient.

Through the experiments conducted, the reference area, A_c was found to be a function of the oscillation frequency (f) and amplitude (θ_I). We will discuss it in detailed in the later section.

With some of the fundamental backgrounds being introduced, we will now proceed to the formulation of the predictive models.

5.3 Predictive Model for Thrust Generation

In this section, mathematical model for the output thrust generated by the fish robot will be developed. The model constructed will be verified by comparing

with the experimental results. This model will then be used in the construction of the swimming speed prediction model in the next section.

5.3.1 Model Formulation

A dimensional analysis technique is used to establish a mathematical relationship to describe output thrust in terms of various parameters, while a regression analysis of the experimental data is undertaken to determine the constants in the models. To simplify the model without losing the generality of the proposed work, the following assumption are made:

- The thrust is being measured under steady swimming speed
- Energy loss through mechanical linkages is negligible
- The thrust is generated through the pressure difference on the sides of the tail fin
- Mechanical losses is negligible (e.g. Input amplitude, θ_I is equal to output amplitude, α_I)
- Amplitude of oscillation (radians) is small, hence $\sin \theta_1 \approx \theta_1$

Studies have shown that the oscillation of the tail causes a pressure difference, P between the sides of the tail fin [12, 15]. Thus, the thrust force can be calculated by:

$$F_{Thrust} = PA_1 \sin \alpha_1 + PA_2 \sin \alpha_2 + PA_3 \sin \alpha_3 \quad (5.2)$$

where A_1 , A_2 , and A_3 are the area (m^2) of the three respective links, while α_1 , α_2 , and α_3 are the angles between three links and the horizontal axis.

The pressure difference, P acting on the three links of the caudal tail fin can be estimated in terms of oscillation frequency, oscillation amplitude, total fin length, caudal fin area, spring constant, movable pin position and flow properties represented by velocity and density [12]. Therefore, only the major and typical variables are considered. The pressure difference, P can be

expressed in the following form:

$$P = \phi(f, \theta, l, \rho_w, \bar{u}, A_3, k, d) \quad (5.3)$$

where f is the oscillation frequency, θ_l is the oscillation amplitude, l is the total fin length, ρ_w is the density of the water, $\bar{u}$ is the average relative velocity, A_3 is area of caudal fin, k is the spring constant at joint 3, and d is the distance between the movable pin position and joint 1.

A dimensional analysis technique is employed to establish the relationship between the various test parameters and the pressure difference generated on the caudal tail fin during the swimming process. With this technique, a relationship between n variables (the physical properties such as velocity, density, etc.) can be expressed as an n - m non-dimensional groups of variables (called π groups) using the constraint that all products formed must have the same dimension, where m is the number of fundamental dimensions (such as mass, length, and time) required to express the variables.

The dimensional analysis is based on Buckingham's theorem [61]. According to Buckingham's theorem, fundamental dimensions m should be first found through the analysis of dimensions of all the variables involved in a problem. Thereafter, we will proceed to select the m repeating variables, which have influences in the problem, to form the n - m dimensionless π groups. Table 5.1 shows the nine variables ($n = 9$), involved in Equation (5.3), with their respective dimension, required to carry out the dimensional analysis for the pressure difference on the caudal tail fin during oscillation.

Table 5.1 Parameters associated with pressure (where L, T and M denote length, time and mass, respectively).

Parameter	Symbol	Dimension
Pressure difference	P	$M/(LT^2)$
Oscillation frequency	f	$1/T$
Oscillation amplitude (radians)	θ_1	-
Total fin length	l	L
Water density	ρ_w	M/L^3
Average relative velocity	$\bar{u}$	L/T
Caudal fin area	A_3	L^2
Spring	k	M/T^2
Movable pin distance	d	L

In Table 5.1, Length (L), mass (M) and time (T) are the fundamental dimensions, and θ_1 is a dimensionless variable. Three repeating variables, l , ρ_w , and f are selected, so that six π groups are formed as follow:

$$\pi_1 = \theta_1 \quad (5.4)$$

$$\pi_2 = \frac{P}{\rho_w f^2 l^2} \quad (5.5)$$

$$\pi_3 = \frac{\bar{u}}{lf} \quad (5.6)$$

$$\pi_4 = \frac{A_3}{l^2} \quad (5.7)$$

$$\pi_5 = \frac{k}{\rho_w f^2 l^3} \quad (5.8)$$

$$\pi_6 = \frac{d}{l} \quad (5.8)$$

Based on Buckingham's π theorem, the original relationship defined in Equation (5.3) can be re-formulated as a function of the dimensionless π groups obtained above. By applying the power law, the pressure difference is given by:

$$P = \rho_w l^2 f^2 \theta^{a_1} \left(\frac{\bar{u}}{lf} \right)^{a_2} \left(\frac{A_3}{l^2} \right)^{a_3} \left(\frac{k}{\rho_w l^3 f^2} \right)^{a_4} \left(\frac{d}{l} \right)^{a_5} \quad (5.10)$$

The relative velocity u is the difference between the flow velocity and the tail velocity (factor v and factor v_t respectively) given by:

$$\vec{u} = \vec{v} - \vec{v}_t \quad (5.11)$$

Hence, the relative velocity in x-direction can be obtained by:

$$u = v + 2\pi f s_1 \theta_1 \cos(2\pi f t) \sin \alpha_1 \quad (5.12)$$

The average velocity can be approximated as:

$$\bar{u} = v + 4f s_1 \theta_1 \quad (5.13)$$

By referring to Figure 3.9 b, the geometry relationship between α_1 and α_2 can be expressed as:

$$\sin \alpha_2 = \frac{s_1 \sin \alpha_1}{\sqrt{s_1^2 + d^2 - 2s_1 d \cos \alpha_1}} \quad (5.14)$$

where s_1 is the length of first link and d is the distance between the movable pin and joint 1.

Since the range of α_1 used in the experiments is relatively small, so based on our assumption, Equation (5.14) can be estimated by:

$$\sin \alpha_2 = c_1 \frac{s_1}{s_1 - d} \sin \alpha_1 \quad (5.15)$$

where c_1 is a coefficient being introduced and will be determined through the regression analysis (refer to section 5.3.2).

Also from the analysis of the kinematics layout in Figure 3.9 b, we can state that:

$$\sin \alpha_3 = \varphi(k, f, \theta_1, d, \bar{u}, \rho_w, A_3) \sin \alpha_1 \quad (5.16)$$

where k is the spring constant and the definition of other variables has been defined previously. All the parameters involved in Equation (5.16) as well as their dimensions are listed in Table 5.2.

Table 5.2 Parameters involved in Equation (5.12) (where L, T and M denote length, time and mass, respectively).

Parameter	Symbol	Dimension
Spring constant	k	M/T^2
Oscillation frequency	f	$1/T$
Oscillation amplitude	θ_1	-
Position of movable pin	d	L
Water density	ρ_w	M/L^3
Average relative velocity	$\bar{u}$	L/T
Area of link 3	A_3	L^2

By using the dimensional analysis method, four π groups can now be formed as follow:

$$\pi_1 = \frac{k}{\rho_w d^3 f^2} \quad (5.17)$$

$$\pi_2 = \theta_1 \quad (5.18)$$

$$\pi_3 = \frac{\bar{u}}{df} \quad (5.19)$$

$$\pi_4 = \frac{A_3}{d^2} \quad (5.20)$$

By applying the power law formulation, we obtained:

$$\sin \alpha_3 = \left(\frac{k}{\rho_w d^3 f^2} \right)^{b_1} \theta_1^{b_2} \left(\frac{\bar{u}}{df} \right)^{b_3} \left(\frac{A_3}{d^2} \right)^{b_4} \sin \alpha_1 \quad (5.21)$$

By substituting Equations (5.10), (5.15) and (5.21) into Equation (5.2), we obtained:

$$F_{Thrust} = P(A_1 + A_2 + A_3) \sin \alpha_1 C \quad (5.22)$$

where

$$C = \left[1 + \frac{c_1 s_1}{s_1 - d} + \left(\frac{k}{\rho_w d^3 f^2} \right)^{b_1} \theta_1^{b_2} \left(\frac{\bar{u}}{df} \right)^{b_3} \left(\frac{A_3}{d^2} \right)^{b_4} \right] \quad (5.23)$$

With the given input oscillation given as:

$$\alpha_1 = \theta_1 \sin 2\pi ft \quad (5.24)$$

The output thrust force can then be expressed as:

$$F_{Thrust} = P(A_1 + A_2 + A_3) \sin(\theta_1 \sin 2\pi ft) C \quad (5.25)$$

It is noted from Equation (5.25) that the thrust force is a time dependent function, the average thrust force can thus be calculated by:

$$\overline{F}_{Thrust} = 2f \int_0^{1/2f} F_{Thrust} dt \quad (5.26)$$

5.3.2 Model Assessment

With the predictive thrust model formulated, we can now proceed to determine the constants in Equation (5.22, 5.10 and 5.23) using regression analysis based on the experimental data found in Chapter 4.

The experimental data from the orthogonal design found in Chapter 4 are used here to determine the constants (the coefficient and exponents) in Equation 5.10 and 5.23. Since there are only 49 runs data from the orthogonal design, a regression analysis of the as-measured data has been carried out to obtain the thrust generated by the caudal tail fin for all the possible combinations (all the levels of the experimental parameters used in the study). The 5184 data (output thrust) from the regression analysis were statistically used to determine the constants in Equation 5.10 and 5.23. By substituting the constants found into Equation 5.10 and 5.23 give:

$$P = \rho_w l^2 f^2 \theta^{11.011} \left(\frac{\bar{u}}{lf} \right)^{8.354} \left(\frac{A_3}{l^2} \right)^{-21.732} \left(\frac{k}{\rho_w l^3 f^2} \right)^{3.955} \left(\frac{d}{l} \right)^{27.661} \quad (5.10a)$$

$$C = \left[1 - \frac{0.229 s_1}{s_1 - d} + \left(\frac{k}{\rho_w d^3 f^2} \right)^{-3.169} \theta_1^{-9.919} \left(\frac{\bar{u}}{df} \right)^{-8.880} \left(\frac{A_3}{d^2} \right)^{22.333} \right] \quad (5.23a)$$

Through further simplification, Equation (5.10a) and (5.23a) become:

$$P = \frac{\theta_1^{11.011} (v + 0.28 f \theta_1)^{8.354} k^{3.955} d^{27.661}}{\rho_w^{2.955} l^{2.416} f^{14.264} A_3^{21.732}} \quad (5.10b)$$

$$C = \left[1 - 0.229 \frac{s_1}{s_1 - d} + \frac{\rho_w^{3.169} f^{15.218} A_3^{22.333}}{k^{3.169} \theta_1^{9.919} d^{26.279} (v + 0.28 f \theta_1)^{8.880}} \right] \quad (5.23b)$$

Substituting the constants such as the water density, $\rho_w = 1000 \text{ kg/m}^3$, area of link 1, $A_1 = 0.00504 \text{ m}^2$, area of link 2, $A_2 = 0.00468 \text{ m}^2$, total fin length, $l = 0.339 \text{ m}$, length of link1, $s_1 = 0.07 \text{ m}$ into Equation (5.10b) and (5.23b) give:

$$P = 18.622 \times 10^{-9} \left[\frac{\theta_1^{11.011} (v + 0.28 f \theta_1)^{8.354} k^{3.955} d^{27.661}}{f^{14.264} A_3^{21.732}} \right] \quad (5.10c)$$

$$C = \left[1 - \frac{0.01603}{0.07 - d} + 3.214 \times 10^9 \left(\frac{f^{15.218} A_3^{22.333}}{k^{3.169} \theta_1^{9.919} d^{26.279} (v + 0.28 f \theta_1)^{8.880}} \right) \right] \quad (5.23c)$$

and finally, we will obtain:

$$F_{Thrust} = PC(0.00972 + A_3) \sin(\theta_1 \sin 2\pi ft) \quad (5.27)$$

By using the Simpson rule, we can then estimate the integrations of F_{Thrust} with high accuracy:

$$\overline{F}_{Thrust} = \frac{2}{3} PC f (9.72 \times 10^{-3} + A_3) \left(8 \sin \frac{\theta_1}{2} + 4 \sin \frac{\sqrt{3}\theta_1}{2} + 4 \sin \theta_1 \right) \quad (5.28)$$

An analysis of the output thrust predicted by the model with respect to the input parameters has been carried out to study the model's generality and plausibility. Meanwhile, by comparing the predicted output thrust with the experimental results, the adequacy of the model's prediction is further assessed. Figure 5.4 to Figure 5.9 show the predicted trends by the developed model and the trends from the experimental results. From the charts, the solid lines represent the predicted data and the experimental results were represented by symbol.

Figure 5.4 Predicted Trends of Thrust ($F_{x-system}$) Generated with respect to Oscillating Frequency.

Figure 5.5 Predicted Trends of Thrust ($F_{x-system}$) Generated with respect to Oscillating Amplitude.

Figure 5.6 Predicted Trends of Thrust ($F_{x-system}$) Generated with respect to Movable Pin Position.

Figure 5.7 Predicted Trends of Thrust ($F_{x-system}$) Generated with respect to Caudal Fin Area.

Figure 5.8 Predicted Trends of Thrust ($F_{x-system}$) Generated with respect to Spring Constant.

Figure 5.9 Predicted Trends of Thrust ($F_{x-system}$) Generated with respect to Flow Velocity.

The figures above show the average predict thrust force with respect to different input parameters. It can be found that the predicted model has a good agreement with the experimental results for most of the parameters.

Figures 5.4 (a) & (b) show the predicted trends of the output thrust generated with respect to the oscillating frequency. It can be noticed that the output thrust increases as the frequency increases. These trends are qualitatively in good agreement with the experimental result (symbols) for frequency range of 0.4 Hz to 2.0 Hz as shown in the figures. However, the predicted values do not tally well with the experimental data at a frequency of 2.4 Hz. The drop in thrust force at frequency of 2.4 Hz may be due to the limitation of the tail fin mechanism, which has not been taken care of by the modeling. However, this model is still adequate to predict the thrust force for most of the cases, especially for the other parameters.

The above qualitative analysis and comparison of the output thrust (predicted values versus experimental values) have shown that the model has accurately predicted the relationship between the output thrust and its input parameters. It can be concluded from this qualitative analysis that the model has been formulated with sufficient accuracy to represent the effect of these variables. Thus, the model can be considered being formulated correctly.

To further assess the adequacy of this model prediction, a quantitative assessment of the model has been carried out based on the percentage deviation of the model predictions, with respect to the experimental results under the testing conditions.

The following equation for the deviation is being used:

$$\%dev. = \frac{\text{predicted.value} - \text{experimental.data}}{\text{experimental.data}} \times 100 \quad (5.29)$$

The histogram in Figure 5.10 shows the percentage deviation of the predicted thrust force with respect to the experimental data in testing. It shows that the model's prediction gives an average percentage derivation of -6.45% with a standard deviation of 27.5%. Therefore, the proposed model in Equation (5.28) can provide an adequate prediction of thrust force.

Figure 5.10 Percentage Deviation

5.4 Predictive Model for Speed Generation

In this section, predictive model for the swimming speed of the fish robot will be developed based on the thrust model and the correction factor discussed earlier. Some general assumptions were also included in developing the model. The predictive model constructed will be verified by comparing with the experimental results.

5.4.1 Model Formulation

The swimming velocity prediction model was built on the predictive thrust model found, the convention drag force equation (Equation 5.1), the correction factor β (Section 4.8.1) and a regression analysis on the experimental data.

To simplify the model without losing the generality of the proposed work, the following assumption were made:

- The fish robot is in steady swimming state
- Energy loss due to external disturbances is negligible
- The fish robot is under constant swimming velocity when the total drag force is equal to the total thrust force, $F_d = \bar{F}_{Thrust}$

- Drag coefficient, C_d is determined experimentally and treated as a constant with a mean value of 0.67

For a fish swimming at a constant speed, its thrust must be sufficient to overcome its drag. Based on our assumption that under constant swimming velocity, $F_d = \bar{F}_{Thrust}$, Equation (5.1) will become:

$$\begin{aligned} F_d &= \frac{1}{2} \rho C_d A_c v_{fix}^2 = \bar{F}_{Thrust} \\ \bar{F}_{Thrust} &= \frac{1}{2} \rho C_d A_c v_{fix}^2 \end{aligned} \quad (5.30)$$

With some manipulation, the ‘Fixed Body’ swimming velocity will be:

$$v_{fix} = \sqrt{\frac{2\bar{F}_{Thrust}}{\rho C_d A_c}} \quad (5.31)$$

By substituting Equation (4.7) into Equation (5.31), the ‘Free Body Motion’ swimming velocity can be expressed as:

$$v_{free} = \beta \sqrt{\frac{2\bar{F}_{Thrust}}{\rho C_d A_c}} \quad (5.32)$$

where β is the correction factor as discussed in Section 4.8.1.

Substituting Equation (5.28) into Equation (5.32), the ‘Free Body Motion’ swimming velocity can be expressed as:

$$v_{free} = \beta \sqrt{\frac{\frac{4}{3} PC_f (9.72 \times 10^{-3} + A_3) (8 \sin \frac{\theta_1}{2} + 4 \sin \frac{\sqrt{3}\theta_1}{2} + 4 \sin \theta_1)}{\rho C_d A_c}} \quad (5.33)$$

5.4.2 Model Assessment

Before going into the assessment of the swimming velocity prediction model, we would like to look at how the values of the reference frontal area (A_c) for various cases were obtained. As shown in Figure 5.11, the reference frontal area, A_c in this study is defined as the multiplication of the maximum peak-to-peak (Q) oscillation of the caudal tail fin and the constant height of the fish robot (R).

Figure 5.11 Reference Frontal Area Approximation

From the experimental data, the reference area, A_c was found to be a function of the oscillation frequency (f) and amplitude (θ_1). Since the height of the fish robot (R) is a constant, this implies that the sweeping amplitude (Q) will change according to the input frequency and amplitude. The general effect of the input frequency (f) and amplitude (θ_1) on the sweeping amplitude (Q) is shown in Figure 5.12.

Figure 5.12 General Effect of Oscillating Frequency (f) and Amplitude (θ_1) on the Sweeping Amplitude (Q)

By using regression analysis, the curve fitting relationship between the sweeping amplitude (Q), oscillating frequency (f), and the oscillating amplitude (θ_l) can be expressed as:

$$Q = -0.126f + 0.016\theta_l - 0.004f\theta_l + 0.042f^2 + 0.00015\theta_l^2 + 0.078 \quad (5.34)$$

where f is frequency of oscillation (Hertz)

θ_l is amplitude of oscillation (Degree)

Thus, the reference frontal areas (A_c) of the fish robot for various cases are approximated using Equation (5.35) with an ‘Adjusted R-Square’ value of 0.991.

$$A_c = R(-0.126f + 0.016\theta_l - 0.004f\theta_l + 0.042f^2 + 0.00015\theta_l^2 + 0.078) \quad (5.35)$$

With the reference frontal area determined, we can now proceed to assess the prediction model for the ‘Fixed Body Motion’ swimming velocity by using Equation (5.31).

(i) ‘Fixed Body Motion’ Swimming Velocity Prediction versus Experimental Results

Figure 5.13 Predicted Trends of the 'Fixed Body Motion' Swimming Velocity as Compared to the Experimental Results

Figures 5.13 (a-d) show the predicted trends of the 'Fixed Body Motion' swimming velocity and the trends from the experimental results. From the charts, the solid lines represent the predicted data and the experimental results were represented by symbol.

It can be noted that the predicted trends agreed well with the experimental results. From the figures, it can be seen that the swimming velocity increases as the amplitude and frequency increases. From these comparisons, we can conclude that the swimming velocity model can adequately predict the 'Fixed Body Motion' swimming speed of the fish robot.

(ii) 'Free Body Motion' Swimming Velocity Prediction versus Experimental Results

The predicted 'Free Body Motion' swimming velocity values for each run can be determined using Equation (5.33). However, we have to find a best-fixed curve to approximate the value of the correction factor (β) for each respective run.

We employed a curve fitting to find a curve the best fit to a series of data points found from the previous experiments (Section 4.8) to predict the value of the correction factor, β . The curve will be expressed in terms of the two major parameters (f and θ_1).

By using regression analysis, the curve-fitting (quadratic) relationship between the correction factor (β), the oscillating frequency (f) and the oscillating amplitude (θ_1) is as follows:

$$\beta = 0.153f - 0.132\theta_1 + 0.002f\theta_1 + 0.015f^2 + 0.004\theta_1^2 + 1.603 \quad (5.36)$$

A suitable curve for the correction factor was found with an adjusted R-square value of 0.923. The assessment on the ‘Free Body Motion’ swimming velocity model was carried out by comparing the predicted swimming velocity with the experimental results as shown in Figure 5.14.

Figures 5.14 (a-d) show the predicted trends of the ‘Free Body Motion’ swimming velocity and the trends from the experimental results. From the charts, the solid lines represent the predicted data and the experimental results were represented by symbol.

It can be noted from Figures 5.14 (a-d) that the predicted trends of the ‘Free Body Motion’ are consistent with the corresponding experimental trends. This result has shows that the model has adequately predicted the swimming velocity of the fish robot. Hence, it can be concluded that the curve-fitting for the approximation of the corrector factor (β) is ample to form the relationship between the ‘Fixed Body Motion’ swimming velocity and the ‘Free Body Motion’ swimming velocity. Thus, we believe that this model can be utilized in future navigation control to improve its positioning capability.

Figure 5.14 Predicted Trends of the 'Free Body Motion' Swimming Velocity as Compared to the Experimental Results

5.5 Summary

In this chapter, predictive models have been developed for the output thrust generated and the swimming velocity of the fish robot. The modeling will start with the construction of predictive output thrust model before progressing to construct the model for swimming velocity prediction.

The application of the dimensional analysis proposed in this study gives a relatively simplified equation to predict the thrust force generated by the tail oscillation. The predicted values are in good agreement with the experimental testing results. The predictive model for the thrust force has been assessed qualitatively and quantitatively by comparing with experimental data under the respective conditions. It has been found that with regards to the thrust force measured in each experiment running, the respective average percentage

deviation for prediction results was -6.45%, while the corresponding standard deviation was 27.5%.

The swimming velocity prediction model is built on the predictive thrust model found earlier, with the use of the fundamental drag force equation and regression analysis on the experimental data. This swimming velocity model is being assessed by comparing with experimental data under corresponding conditions. It can be concluded from the qualitative analysis that the model has been formulated with sufficient accuracy to predict the swimming velocity of the fish robot.

With the models being able to adequately predict the output thrust and swimming velocity, we believe that it will be a very useful input to future navigation control of the fish robot. Especially in the inertial navigation control, where the sensors input can be compared with this prediction data to reduce its positioning error.

In future, this semi-empirical method can also be applied for the performance prediction model for median and/or paired fin (MPF) biomimetic fish robots.

CHAPTER 6: CONCLUSION AND FUTURE WORKS

6.1 Concluding Remarks

A modular BCF type of bio-mimetic fish robot had been developed using mechatronics principles. This fish robot serve as a research platform for research of numerous disciplines to be undertaken includes more in-depth experimental studies, underwater wireless communications, navigation control and localization, and high-level adaptive control system based on artificial central pattern generation (CPG).

Parametric experimental studies on the various parameters (f , θ_l , D , r , k , v) have been carried out. From the studies, a combination of a relatively high frequency (2.0 Hz), a sweeping amplitude (Q) to fish's length ratio of about 0.1-0.12, a high aspect ratio (8.71), a movable pin position at ' $D4$ ' (nearest to joint 1) and a softer spring (0.98 N/mm) can produce the largest thrust force. The analysis of the interaction $f*\theta_l$ has shown that under the same sweeping velocity a higher thrust can be generated with a lower frequency and larger amplitude as compare to a higher frequency and lower amplitude. Additional experiments conducted to study the effect on the spring constant on the output thrust alone, have indicated a sign of drag reduction.

Experiments on the speed-thrust relationship have shown that for the same thrust generated, the one with high frequency is able to swim at a higher speed. The Strouhal analysis showed that the efficiency of current system is low, which is mainly due to the high body drag of Nanyang Awana (NAF-I).

During the field test, the NAF-I is capable of swimming up to a speed of 19.8 m/min (1/2 a body length per second) under outdoor condition, which is significantly greater than NAW-I (earlier version) by a factor of six. Moreover, there is a sign of potential drag reduction when we compared the field test result with the water-tunnel result.

The results from the ‘Fixed Body Motion’ and ‘Free Body Motion’ swimming velocity comparison have shown that the body motion of the fish robot and the oscillating frequency has influences on its overall swimming velocity. The sign of potential drag reduction is more obvious when the oscillating frequency is above 1.6 Hz where the fish’s body yawing motion is smaller as compared to that of the lower oscillating frequency. Hence, a certain degree of flexibility of the fish’s body is essential to reduce the yawing effect of the fish robot’s body, especially under lower oscillating frequencies.

Predictive models have been developed for the output thrust generated and the swimming velocity of the fish robot. It can be concluded from the qualitative analysis that the models have been formulated with sufficient accuracy to predict the output thrust and swimming velocity of the fish robot. We believe that it will be a useful input to future navigation control of the fish robot. Especially in the inertial navigation control, where the sensors input can be compared with this prediction data to reduce its positioning error.

6.2 Proposed Future Works

From the investigations carried out and reported in this thesis, a few possible future avenues of research derived immediately from this work can be suggested.

1. System Design Improvement

Results from the computation fluid dynamic (CFD) simulations (Section 4.6.3) have also proved that a more streamline fish’s body will significantly reduce the body drag especially at high flow velocity. Hence, if the fish robot has perfectly streamline body, it will be able to operate in the desire Strouhal range of 0.2 to 0.4 where maximum efficiency occurs. A possible solution to reduce the overall body drag of

current design have been proposed as shown in Figure 6.1. A slight modification and parts were added to the existing design without the need to change the whole body of the fish robot.

Figure 6.1 Cad Model of Fish Robot (Current and Improved Design).

As can be seen in Figure 6.1, several eclipse supports were added to the tail fin mechanism. A neoprene rubber skin will be placed over these eclipse supports to make the end part of the fish robot more streamline. This neoprene rubber skin creates a smooth flexible surface at the fish tail which will significantly reduce the overall drag of the fish robot.

The results from the ‘Fixed Body Motion’ and ‘Free Body Motion’ swimming velocity comparison have show that the body motion of the fish robot and the oscillating frequency has influences on its overall swimming velocity. Hence, a certain degree of flexibility is essential in the future to increase the swimming performance of the fish robot.

Thus, in the future, the existing body of NAF-I can be made more streamline and an additional degree of freedom can be added to it to increase its flexibility. As, based on our studied, we will need to have a more streamline (see Figure 4.20 and 4.21) and flexible body to increase the overall efficiency.

2. Develop Adaptive Control System

Develop a practical force feedback method for the control system. The feedback information will be part of the inputs for a self gait generation system. The output thrust predictive model can also be used as a feedback input to the control system to enhance its positioning control. Future research should study and find the discipline of this force/power distribution. The results will make a great impact on the full feedback swimming control system for fish robot.

3. Modeling on a Median and/or Paired Fin (MPF) type of propulsion

The modeling of the Body and/or Caudal Fin (BCF) swimming propulsion using the semi-empirical method has obtained with sufficiently good results. It is hope that the same semi-empirical method can also be applied for the performance prediction model for median and/or paired fin (MPF) biomimetic fish robots.

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Appendix A

Detailed Technical Drawing for NAF-I

Appendix B

Buoyancy Calculation

Appendix C

Experimental Procedure

Appendix D

Construction of Caudal Fins

Buoyancy Force Calculation (refer to Section 3.1)

A buoyancy tank has been incorporated onto the fish, thus it is important to know the buoyancy of the fish. The aim is to get the fish to neutral buoyant when the piston of the buoyancy tank is fully extended, so when the piston contract the fish will sink to the required depth. The following shows an estimated buoyancy calculation for the fish.

Calculation based on the formula of Archimedes.

Figure B-1 Basic Buoyancy Layout

Buoyancy force => $F_B = \rho_f g V_f$

Weight of body => $F_G = \rho_b g V_b$

Legend:

ρ_f	Density of fluid (Water = 1000kg/m ³)
V_f	Volume of displaced fluid
ρ_b	Density of body
V_b	Volume of body
g	Gravity acceleration 9.81m/s ²

The fish is divided into 3 main units (Head, Body and Tail) for the buoyancy analysis. Figure B-2 shows the layout of the three main units and the forces acting on it. In order to calculate the g-force of the individual components, the mass of each component must be known and is tabulated in Table 3.4.

Figure B-2 Buoyancy Forces on the Three Main Unit

Table B-1 Mass of individual components for Fish Robot

	HEAD	BODY	TAIL	FISH (TOTAL)
Volume displaced in water [m ³]	1.441 x 10 ⁻³	3.924 x 10 ⁻³	0.291 x 10 ⁻³	5.657 x 10 ⁻³
Mass of unit [kg]	1.38	4.28	0.48	6.135

Head:

$$F_{B,Head} = 1000 \frac{kg}{m^3} \cdot 9.81 \frac{m}{s^2} \cdot 0.001441 m^3 = 14.137 N$$

$$F_{G,Head} = 1.38 kg \cdot 9.81 \frac{m}{s^2} = 13.538 N$$

$$\rightarrow \underline{F_{B,Head} > F_{G,Head}}$$

Body:

$$F_{B,Body} = 1000 \frac{kg}{m^3} \cdot 9.81 \frac{m}{s^2} \cdot 0.003924 m^3 = 38.494 N$$

$$F_{G,Body} = 4.28 kg \cdot 9.81 \frac{m}{s^2} = 41.987 N$$

$$\rightarrow \underline{F_{B,Body} < F_{G,Body}}$$

Tail:

$$F_{B,Tail} = 1000 \frac{kg}{m^3} \cdot 9.81 \frac{m}{s^2} \cdot 0.000291 m^3 = 2.845 N$$

$$F_{G,Tail} = 0.48 kg \cdot 9.81 \frac{m}{s^2} = 4.701 N$$

$$\rightarrow \underline{F_{B,Tail} < F_{G,Tail}}$$

Fish:

$$F_{B,Head} = 1000 \frac{kg}{m^3} \cdot 9.81 \frac{m}{s^2} \cdot 0.005657 m^3 = 55.495 N$$

$$F_{G,Head} = 6.135 kg \cdot 9.81 \frac{m}{s^2} = 60.184 N \quad \rightarrow \quad \underline{F_{B,Head} < F_{G,Head}}$$

From the above results, the buoyancy force is slightly lower than the weight of body; this means that the fish will sink if it is placed in the water. To achieve neutral buoyancy, some blue-foam needs to be attached onto the fish body.

Appendix C-1

The table below shows the 109 experimental runs conducted in Section 4.4.

Run No.	f (Hz)	θ_l (°)	D	r	k (N/mm)	v (m/s)
1	1.2	16	2	8.71	4.61	0.0348
2	1.2	10	2	8.71	2.45	0.1708
3	2	16	1	4.8	4.61	0.0348
4	0.4	14	3	3.21	2.45	0.0348
5	1.6	6	2	3.21	2.45	0.0348
6	2.4	8	2	4.8	2.45	0.0348
7	2	12	3	8.71	2.45	0.0348
8	1.2	8	1	3.21	0.98	0.1028
9	2.4	6	4	8.71	0.98	0.0348
10	1.2	6	4	4.8	0.98	0.1028
11	0.4	16	1	8.71	2.45	0.1028
12	0.8	10	1	3.21	0.98	0.0348
13	1.6	6	1	4.8	2.45	0.1708
14	0.4	16	2	6.82	0.98	0.0348
15	0.4	14	1	8.71	4.61	0.1708
16	1.6	12	1	4.8	0.98	0.1028
17	0.8	6	1	8.71	2.45	0.1708
18	1.2	6	3	6.82	0.98	0.0348
19	0.4	6	1	8.71	0.98	0.0348
20	2.4	10	3	8.71	4.61	0.1028
21	2.4	6	1	6.82	2.45	0.0348
22	0.4	8	2	6.82	2.45	0.1028
23	2.4	14	2	4.8	0.98	0.1708
24	2.4	12	1	6.82	4.61	0.1028
25	2	10	2	4.8	0.98	0.1708
26	2	14	4	6.82	2.45	0.0348
27	0.4	10	3	4.8	2.45	0.1028
28	0.4	6	2	6.82	4.61	0.1028
29	0.4	12	2	4.8	0.98	0.0348
30	1.2	12	3	6.82	2.45	0.1708
31	0.4	8	4	8.71	0.98	0.1708
32	0.8	6	2	6.82	4.61	0.1708
33	0.8	14	3	6.82	0.98	0.1028
34	0.4	6	3	4.8	0.98	0.0348
35	0.4	12	4	3.21	4.61	0.1708
36	2	8	1	8.71	0.98	0.1708
37	2	6	2	3.21	4.61	0.1028
38	0.4	10	1	6.82	0.98	0.0348
39	1.2	14	1	4.8	4.61	0.0348
40	0.8	8	3	4.8	4.61	0.0348
41	0.4	6	3	4.8	4.61	0.1708
42	1.6	14	2	8.71	0.98	0.1028
43	1.6	8	3	8.71	4.61	0.0348
44	1.6	16	3	6.82	0.98	0.1708
45	2	6	3	8.71	0.98	0.1028
46	2.4	16	3	3.21	0.98	0.1708
47	1.6	10	4	6.82	4.61	0.0348
48	0.8	16	4	4.8	2.45	0.1028
49	0.8	12	2	8.71	0.98	0.0348
50	0.4	6	3	3.21	2.45	0.0348
51	0.4	8	3	3.21	2.45	0.0348
52	0.4	10	3	3.21	2.45	0.0348
53	0.4	12	2	3.21	2.45	0.0348
54	0.4	14	2	3.21	2.45	0.0348
55	0.4	16	1	3.21	2.45	0.0348
56	0.4	6	3	8.71	2.45	0.1028
57	0.4	8	2	8.71	2.45	0.1028
58	0.4	10	2	8.71	2.45	0.1028
59	0.4	12	3	8.71	2.45	0.1028
60	0.4	14	1	8.71	2.45	0.1028
61	0.4	16	4	8.71	2.45	0.1028
62	0.4	8	4	4.8	2.45	0.0348

Run No.	f (Hz)	θ_1 (°)	D	r	k (N/mm)	v (m/s)
63	0.8	8	1	4.8	2.45	0.0348
64	1.2	8	1	4.8	2.45	0.0348
65	1.6	8	1	4.8	2.45	0.0348
66	2	8	2	4.8	2.45	0.0348
67	2.4	8	1	4.8	2.45	0.0348
68	0.4	10	1	3.21	0.98	0.0348
69	0.8	10	1	3.21	0.98	0.0348
70	1.2	10	3	3.21	0.98	0.0348
71	1.6	10	1	3.21	0.98	0.0348
72	2	10	3	3.21	0.98	0.0348
73	2.4	10	1	3.21	0.98	0.0348
74	0.4	6	2	3.21	0.98	0.0348
75	0.8	6	2	3.21	0.98	0.0348
76	1.2	6	1	3.21	0.98	0.0348
77	1.6	6	2	3.21	0.98	0.0348
78	2	6	4	3.21	0.98	0.0348
79	2.4	6	3	3.21	0.98	0.0348
80	0.4	12	2	4.8	0.98	0.0348
81	0.4	12	2	4.8	0.98	0.0348
82	0.4	12	3	4.8	0.98	0.0348
83	0.4	12	4	4.8	0.98	0.0348
84	0.8	8	2	4.8	4.61	0.0348
85	0.8	8	3	4.8	4.61	0.0348
86	0.8	8	3	4.8	4.61	0.0348
87	0.8	8	4	4.8	4.61	0.0348
88	0.4	8	1	4.8	0.98	0.0348
89	0.4	8	2	4.8	0.98	0.0348
90	0.4	8	1	4.8	0.98	0.0348
91	0.4	8	1	4.8	0.98	0.0348
92	1.2	12	3	4.8	0.98	0.0348
93	1.2	12	3	4.8	0.98	0.0348
94	1.2	12	2	4.8	0.98	0.0348
95	1.2	12	3	4.8	0.98	0.0348
96	0.8	14	3	6.82	0.98	0.0348
97	0.8	14	3	6.82	0.98	0.1028
98	0.8	14	3	6.82	0.98	0.1708
99	1.6	8	4	8.71	4.61	0.0348
100	1.6	8	4	8.71	4.61	0.1028
101	1.6	8	2	8.71	4.61	0.1708
102	0.8	10	3	8.71	0.98	0.0348
103	0.8	10	3	6.82	0.98	0.0348
104	0.8	10	3	4.8	0.98	0.0348
105	0.8	10	3	3.21	0.98	0.0348
106	1.6	10	3	8.71	0.98	0.0348
107	1.6	10	3	6.82	0.98	0.0348
108	1.6	10	1	4.8	0.98	0.0348
109	1.6	10	1	3.21	0.98	0.0348

Appendix C-2

Experimental Procedure for Section 4.4

Equipment: ATI force transducer, water-tunnel system, and personal computer.

Experimental Parameter: frequency (f), amplitude (a), movable pin position (d), aspect ratio (r), spring constant (k) and water flow rate (v)

Procedure:

1. Attached the force sensor onto the fixture above the water tank. Insert the connecting rod onto to force sensor.
2. Attached the fish robot onto the other end of the connecting rod gently. Ensure the fish is well aligned with the flow stream.
3. Turn on the radio transmitter on the PC and start the control interface program.
4. Turn on the power supply to the fish robot.
5. Press the reset button on the prototype to initialize the home position.
6. Set the run parameters (f, A, D, r, k, v) according to Table in Appendix C-1.
7. Turn on the water pump of the water tunnel and wait for 5 min to allow the flow to stabilize.
8. Bias the flow sensor reading to zero, so that the drag force of the body and the connecting rod will not be considered in the force reading.
9. Start the motion of the fish robot by using the control interface.
10. Wait for 5 oscillating cycle.
11. Run the force sensor data acquisition program to record the force generated for the next 30 cycles.
12. Stop the force sensor data acquisition program and save the result.
13. Stop the motion of the fish robot by using the control interface.
14. Wait for 2 minutes to allow the water to stabilize from the previous run.
15. Repeat Step 8 to 14 for 3 sets of reading.
16. Turn off the water pump of the water tunnel.
17. Record the mean value from the 3 readings.
18. Repeat Step 5 to 17 for the remaining runs.

Appendix C-3

Experimental Procedure for Section 4.5

Equipment: ATI force transducer, water-tunnel system, and personal computer.

Experimental Parameter: frequency (f), amplitude (a), movable pin position (D) with $k = 0.98\text{N/mm}$, $v = 0.0348\text{m/s}$ and $r = 8.71$.

Procedure:

1. Attached the force sensor onto the fixture above the water tank. Insert the connecting rod onto to force sensor.
2. Attached the fish robot onto the other end of the connecting rod gently. Ensure the fish is well aligned with the flow stream.
3. Turn on the radio transmitter on the PC and start the control interface program.
4. Turn on the power supply to the fish robot.
5. Press the reset button on the prototype to initialize the home position.
6. Set the run parameters (f,A,D) according to Table 4.6.
7. Turn on the water pump of the water tunnel and wait for 5 min to allow the flow to stabilize.
8. Bias the flow sensor reading to zero, so that the drag force of the body and the connecting rod will not be considered in the force reading.
9. Start the motion of the fish robot by using the control interface.
10. Wait for 5 oscillating cycle.
11. Run the force sensor data acquisition program to record the force generated for the next 30 cycles.
12. Stop the force sensor data acquisition program and save the result.
13. Stop the motion of the fish robot by using the control interface.
14. Wait for 2 minutes to allow the water to stabilize from the previous run.
15. Repeat Step 8 to 14 for 3 sets of reading.
16. Turn off the water pump of the water tunnel.
17. Record the mean value from the 3 readings.
18. Repeat Step 5 to 17 for the remaining runs.

Appendix C-4

Experimental Procedure for Section 4.6

Equipment: ATI force transducer, water-tunnel system, and personal computer.

Experimental Parameter: frequency (f), amplitude (a) and water flow rate (v)

Procedure:

1. Attached the force sensor onto the fixture above the water tank. Insert the connecting rod onto to force sensor.
2. Attached the fish robot onto the other end of the connecting rod gently. Ensure the fish is well aligned with the flow stream.
3. Turn on the radio transmitter on the PC and start the control interface program.
4. Turn on the power supply to the fish robot.
5. Press the reset button on the prototype to initialize the home position.
6. Set the run parameters (f,A).
7. Bias the force sensor reading to zero.
8. Start the motion of the fish robot by using the control interface.
9. Wait for 5 oscillating cycle.
10. Run the force sensor data acquisition program to record the force generated for the next 30 cycles.
11. Stop the force sensor data acquisition program and save the result.
12. Repeat step 10 and 11 for two more times.
13. Average the three reading obtained from step 10 to 12 to get the mean thrust force of the oscillating fin ($F_{\text{Net.Tail}}$).
14. Turn on the water-tunnel flow pump.
15. Slowly increase the water-tunnel flow velocity until the reading of the force sensor is zero.
16. Record down the velocity (in Hz) of the water-tunnel flow.
17. Turn off the water-tunnel flow pump.
18. Stop the motion of the fish robot and set it to home position by using the control interface.
19. Wait for 2 minutes to allow the water to stabilize from the previous run.
20. Repeat Step 6 to 19 for the remaining runs.

Appendix D

Figure C-1 Caudal Fins Design

As mention in Section 4.4.3 (ii), the aspect ratio (r) of the caudal fins as shown in Figure C-1 is defined by H^2/A , where H is the vertical height between the two tip ends and A is the area of the fin surface (shaded blue region as shown in Figure C-1).

Four arcs (r_1, r_2, r_3, r_4) and a short vertical line construct the caudal fin. Figure C-1 (a) shows the first two arcs (r_1 and r_2) used in the construction where the other two arcs (r_3 and r_4 , which are symmetric sides of r_1 and r_2 were not labeled in the figure).

The four different aspect ratio caudal fins (used in the parametric study in chapter 4) was constructed by changing the dimension of the caudal width (CW) while keeping the centre distance between the four arcs (CD_1, CD_2, CD_3 and CD_4) and vertical height between two tips ends (H) as constant. Note that the dimensions of the four arcs are dependent on the caudal width (CW). By changing the caudal width while keeping the other independent dimensions constant, will results in the change of caudal area (see Figure C-1 (b)) and thus, the aspect ratio.