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B. Eng, 2018

FLOW FIELD MEASUREMENT OF FISH AND DEVELOPMENT OF FISH LIKE UNDERWATER ROBOT

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2018

FLOW FIELD MEASUREMENT OF FISH AND DEVELOPMENT OF FISH LIKE UNDERWATER ROBOT

by

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Thesis submitted in fulfilment of the requirements for the
Bachelor Degree of Engineering (Honours) (Aerospace Engineering)

June 2018

ENDORSEMENT

I, Soh Ling Xin hereby declare that all corrections and comments made by the supervisor and examiner have been taken consideration and rectified accordingly.

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Date:

DECLARATION

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

(Signature of Student)

Date:

ACKNOWLEDGEMENTS

First, I wish to express my enormous gratitude towards my supervisor, Dr Norizham bin Abdul Razak for his valuable guidance and support along the journey of final year project. He is the one who always willing to spare his time and energy constantly for helping. Besides, he is kind to share his expertise for me to grow the new understanding.

Secondly, I am grateful to School of Aerospace Engineering, USM for providing me with all the necessary facilities and apparatus for the research. Then, I place on record my sincere thank you to the technicians especially Mr Mahmud Bin Isa and Mr Nor Ridwan bin Mohamed Yusuf for lending his hands when having any difficulties in lab.

Next, I wish to express my sincere thanks to Mr Lai Hoong Chuin whom master student of Dr Norizham. I am thankful and indebted to him for sharing his knowledge and lending his hand in certain occasions.

In addition, I would like to show my appreciation towards the Silver Mountain (Opaline Gourami) and Gold Mountain (Gold Gourami) for joining in this experiment. Without them, I would not complete my experiment and get the results. Lastly, I take this opportunity to express gratitude to all who had assisted and supported me through this venture.

FLOW FIELD MEASUREMENT OF FISH AND DEVELOPMENT OF FISH LIKE UNDERWATER ROBOT

ABSTRACT

Biomimetic systems had been an advancement to apply in robotic field. The development of the underwater robot requires the study of locomotion and flow around the swimming fish. Therefore, for the development of an aquatic robotic necessitate the investigation of live fish locomotion since it's manoeuvrability and efficiency is excellent. The work presented in this thesis aimed to visualise flow of mechanical fish tail which is designed and fabricated for having the mechanism which similar locomotion as alive fish. Firstly, the swimming Gold Gourami and Opaline Gourami fishes are visualized, especially the vortex shedding produced when fishes propelled. Next, the design and fabrication of water channel has been done before hand to undergo the flow visualisation of Gourami fishes and mechanical fish tail. The experiment will be conducted in two stages where the first stage will be the observation of tail kinematic and visualization flow behind tail of Gourami fishes under water-still condition. Then, the design and fabricate of the mechanical fish tail extract from the data of visualization alive fishes will be done. Thus, the second stage will be the flow visualization of mechanical fish tail. The method of visualization will be Particle Image Velocimetry (PIV). The water flow in water channel is laminar with velocity of 0.28m/s to undergoes the experiment. Body of Gourami fish will bend into S-shaped for sudden speed up and C-shaped for steady swimming. The steady swimming of Gourami fishes shows the vortex chain produced behind the fish tail. The higher the frequency of flapping fish tail will increase the number of vortices produced by the Gourami fish. Hence, the vortex chain would be longer. The vortex chain pattern produced by flapping amplitude of 20 ° was having the highest similarity with Gourami fish compared to 40 ° and 60 °.

PENGUKURAN ALIRAN IKAN DAN PEMBANGUNAN ROBOT SELAM SERUPA IKAN

ABSTRAK

Sistem biomimetic telah menjadi trend yang popular dalam bidang robotik. Pembangunan robot dalam air memerlukan kajian pergerakan dengan aliran di sekitar ikan yang sedang berenang. Oleh itu, pembangunan robot akuatik memerlukan penyelidikan mengenai pergerakan ikan benar yang mudah alih dan berkesan. Kerja-kerja yang dibentangkan dalam tesis ini bertujuan untuk menggambarkan aliran ekor ikan mekanikal yang direka bentuk untuk mempunyai mekanisme yang sama seperti ikan hidup. Pertama, ikan Gold Gourami dan ikan Opaline Gourami divisualisasikan, terutamanya pusaran-pusaran yang dihasilkan apabila ikan berenang. Seterunya, reka bentuk dan fabrikasi saluran air untuk eksperimen menvisualisasikan aliran ikan Gourami dan ekor ikan mekanikal. Eksperimen ini akan dijalani dalam dua peringkat. Peringkat pertama merupakan pemerhatian aliran kinematic ekor dan visualisas aliran di belakang ekor ikan Gourami dalam keadaan air yang tenang. Kemudian, reka bentuk dan pembuatan tail ekor ikan mekanik dari data visualisasi aliran ikan hidup akan dilakukan. Seterusnya, peringkat kedua adalah visualisasi aliran belakang ekor ikan mekanikal. Kaedah Velocimetry Image Partikel (PIV) telah digunakan sebagai kaedah visualisasi. Aliran air dalam saluran air adalah laminar dengan halaju 0.28m / s untuk menjalani eksperimen visualisasi. Badan ikan Gourami akan membengkok berbentuk S untuk kelajuan mendadak dan berbentuk C untuk berenang mantap. Ikan Gourami yang berenenag dengan mantap menunjukkan rantai vorteks yang dihasilkan di belakang ekor ikan. Semakin tinggi kekerapan ekor ikan mengepak akan meningkatkan jumlah vorteks

yang dihasilkan oleh ikan Gourami. Oleh itu, rantaian vorteks akan lebih lama. Corak rantai vorteks yang dihasilkan oleh gepakan dalam amplitudo 20 ° mempunyai persamaan rantai vortex yand dihasilkan oleh ikan Gourami berbanding dengan amplitude 40 ° dan 60 °.

TABLE OF CONTENTS

ENDORSEMENT i
DECLARATION ii
ACKNOWLEDGEMENTS iii
ABSTRACT iv
ABSTRAK vi
LIST OF FIGURES x
LIST OF TABLES xii
LIST OF ABBREVIATIONS xv
LIST OF SYMBOLS xvi

CHAPTER 1: INTRODUCTION 1
- 1.1 Motivation 1
- 1.2 Problem Statement 3
- 1.3 Objectives 4
- 1.4 Research approach and scopes 5
- 1.5 Thesis outline 7

CHAPTER 2: LITERATURE REVIEW 8
- 2.1 Theory 8
  - 2.1.1 Mechanism involved in fish swimming 8
  - 2.1.2 Production of Vortices 9
  - 2.1.3 Idealized Vortex Pattern (Karman Vortex Street) 11
  - 2.1.4 Structure of Vortex 12
  - 2.1.5 Evolution of Vortex 14
- 2.2 Previous Studies 15
  - 2.2.1 Research on flow field measurement of fishes 15
  - 2.2.2 Research on mechanical fish 18
- 2.3 Experimental Studies 21
  - 2.3.1 Water channel design 21
  - 2.3.2 Particle Image Velocimetry (PIV) 23

CHAPTER 3: METHODOLOGY 26
- 3.1 Selection of fish species & fish feeding 27
- 3.2 Fabrication of water channel 29
  - 3.2.1 Assembly of water channel 29

3.2.2 Water pump and piping 31
3.2.3 Water leakage testing and laminar flow setting 32
3.3 Experiment Works 34
3.3.1 Dye injection flow visualization of water channel 34
3.3.2 Experimental set-up for PIV measurement 35
3.3.3 Experimental Set-Up of tail kinematic Gourami fishes 36
3.3.4 Flow measurement of Gourami Fishes 37
3.4 Fabrication of mechanical fish tail 38
3.4.1 Electronic device 41
3.4.2 Electronic system 42
3.5 Flow measurement of mechanical fish 43

CHAPTER 4: RESULT AND DISCUSSION 45
4.1 Flow Visualization of Water Channel 45
4.1.1 Dye injection flow visualization of water channel 45
4.1.2 PIV measurement flow visualization of water channel 47
4.2 Observation of tail kinematic gourami fishes 48
4.3 Flow measurement of gourami fishes 51
4.4 Flow measurement of mechanical fish 55
4.5 Comparison of flow in Gourami and Mechanical fish 61

CHAPTER 5: COCLUSION AND RECOMMENDATIONS 62
5.1 Conclusion 62
5.2 Limitations 62
5.3 Recommendations 63

REFERENCES 65
APPENDICES 69
APPENDIX A. Water channel fabrication process 69
APPENDIX B. Catia drawing of water channel 72
APPENDIX C. Catia drawing of mechanical fish 74
APPENDIX D. Arduino coding for flapping amplitude of mechanical fish tail76

LIST OF FIGURES

Figure 1.1: Opaline Gourami (left) and Gold Gourami fish (right) 5

Figure 1.2: PIV experimental set-up (Babu et al., 2016) 6

Figure 2.1: Parts of fish which function in swimming and thrust generator (Sfakiotakis et al., 1999a) 8

Figure 2.2: The forces acting on a swimming fish adapted from (Magnuson, 1978) 9

Figure 2.3: Schematic diagram of front and top view where exact tracing from photograph (Rosen, 1959) 10

Figure 2.4: Idealized vortex pattern of fish when swimming (Rosen, 1959) 11

Figure 2.5: The wake of swimming fish associated with thrust generation has reverse rotational direction (Sfakiotakis et al., 1999a) 12

Figure 2.6: Water velocity vector field in perpendicular from the pectoral fin from PIV measurement (Drucker and Lauder, 2000) 12

Figure 2.7: Side view of vortices of fish for connected vortex necklace system (Rosen, 1959) 13

Figure 2.8: The flow field around the body of swimming fish, as P and S corresponding to pressure and suction zone which form the basis of "undulating pump" mechanism (Müller et al., 1997) 14

Figure 2.9: Pressure and forces of the fish vortex as a function of age (Rosen, 1959) 14

Figure 2.10: Example of velocity vectors around a turning fish (Sakakibara et al., 2004) 16

Figure 2.11: Prototype of soft-body robot fish (Rus and Tolley, 2015) 19

Figure 2.12: Motion modes of S and C shapes (Liao et al., 2014) 21

Figure 2.13: Wire-driven flapping propulsor design (Li et al., 2013) 21

Figure 2.14: Exploded view of water tunnel (Zahari and Dol, 2015) 22

Figure 2.15: Actual assembly of water tunnel (Kalyankar *et al.*, 2015) 23

Figure 2.16: Schematic Diagram of typical PIV Setup (Brossard et al., 2009) 24

Figure 3.1: Flow chart of methodology 26

Figure 3.2: Water pump table in the store of Aerodynamic Lab 2 29

Figure 3.3: 2D Drawing of water channel by using CATIA 29

Figure 3.4: Assembled water channel 30

Figure 3.5: Design of PVC Pipeline for Connection of Water Pump with Water Channel and Water Pump Table 32

Figure 3.6: Water channel table with (left) SEA Pump Model DB-330 and (right) Pedrollo Model D5-05 (Pump CPM 130) 33

Figure 3.7: Arrangement of honeycomb in test section of water channel 33

Figure 3.8: Schematic diagram of experimental setup for dye flow visualization 34

Figure 3.9: Real experimental Set-up (Above) and schematic diagram of the experimental set-up (bottom) 35

Figure 3.10: Schematic diagram of experimental set-up for observation of tail kinematic 36

Figure 3.11: Schematic diagram of experimental set-up for flow measurement of Gourami fish 37

Figure 3.12: Opaline Gourami (left) and Gold Gourami (right) in water channel 38

Figure 3.13: The dimensions of the mechanical fish tail 39

Figure 3.14: Front view of wood stick vertebrate in 40mm length 39

Figure 3.15: Top view (left) and side view (right) of the mechanical fish 40

Figure 3.16: Diagram of servo motor SG90 41

Figure 3.17: Diagram of Arduino Nano 41

Figure 3.18: Arduino Nano with Nano Terminal Adaptor 42

Figure 3.19: Schematic diagram for connection wires of Arduino Nano and servo motor 42

Figure 3.20: Schematic diagram of experimental set-up for flow measurement of mechanical fish 43

Figure 3.21: The position of the mechanical fish inside the water channel in overview (left) and closer view (right) 44

Figure 4.1: Flow visualization for a piece of honeycomb 46

Figure 4.2: Flow visualization for two pieces of honeycomb 46

Figure 4.3: Flow visualization for three pieces of honeycomb 47

Figure 4.4: Water flow of the water channel in speed of 0.28m/s (left) and 0.14m/s (right) 47

Figure 4.5: Evolution of flow behind the swimming Opaline Gourami 53

Figure 4.6: Evolution of flow behind the swimming Gold Gourami 55

Figure 4.7: Evolution of flow at flapping amplitude of 20 ° 57

Figure 4.8: Evolution of flow at flapping amplitude of 40 ° 59

Figure 4.9: Evolution of flow at flapping amplitude of 60 ° 60

Figure 4.10: Flow measurement of Opaline Gourami (left) and mechanical fish (right) 61

Figure A. 1: The sketching dimensions on Perspex with ruler and marker pen 69

Figure A. 2: The cutting of perspex by using hand-held circular saw (left) and table saw at Robotic & Welding Lab (right) 69

Figure A. 3: Holes at water channel (left) and water pump table (right) 70

Figure A. 4: Wooden plate is painted with black colour (left) and screwed at four different corner (right) 70

Figure A. 5: Usage of white tape (a), rubber gasket (b) and solvent cement (c) during PVC pipe assembly 70

Figure A. 6: Wooden plate is painted with black colour (left) and screwed at four different corner (right) 71

Figure A. 7: SEA pump model DB-330 (left) and Pedrollo model D5-05 (Pump Cpm 130) (right) 71

Figure B. 1: 2D drawing of water channel 72

Figure B. 2: 2D drawing of assembly water channel with water pump table 73

Figure C. 1: 2D drawing of mechanical fish tail 74

Figure C. 2: BOM of 2D drawing mechanical fish tail 75

LIST OF TABLES

Table 2.1: Previous studies of fishes by using PIV (Deng *et al.*, 2004) 25

Table 3.1: Comparison of different species of fishes 27

Table 3.2: Types of PVC Pipe injection and adhesive purchased with amount 31

Table 3.3: Arrangement of honeycomb in experiment 35

Table 4.1: Analysis for tail kinematic of Opaline Gourami 49

Table 4.2: Analysis for tail kinematic of Gold Gourami 50

LIST OF ABBREVIATIONS

PIV : Particle Image Velocimetry

SCPIV : Sub-image Correlation Particle Image Velocimetry

CCD : Coupled charged devices

2D : Two Component

DC : Direct Current

LED : Light Emitting Diode

PVC : Poly Vinyl Chloride

LIST OF SYMBOLS

[illegible] : Reynolds number

[illegible] : time

CHAPTER 1

INTRODUCTION

1.1 Motivation

Biomimetic systems have been the focus of research in the robotics field for a long time. The natural world provides a large body of biomimetic knowledge where engineers could replicate and apply the lesson learned on the mechanism of the robotic field. There are many studies which related to the undulating motion of swimming fish (Sfakiotakis *et al.*, 1999b, Sheu and Chen, 2007). Kinematic study and flow field measurement and of live fish could lead to the design of efficient propulsion mechanism for underwater robot. The focus lies on the study of the fish body locomotion and tail to generate the undulatory motion which propels them.

Lighthill and Wu researched on slender body theory of swimming fish to obtain the efficiency of fish propulsion in water (Sakakibara *et al.*, 2004, Sheu and Chen, 2007). Vortices that were produced by the undulating swimming fishes could helped saves energy required for propulsion. Thus, the locomotion of live fishes undulatory motion generates the thrust required for fish to swim effectively. Theory of fish locomotion for forward motion and turning is important aspects of knowledge that could be applied to underwater robot propulsion system.

Development of the underwater robotic field has been popular nowadays, especially in undersea operation, oceanic supervision, aquatic life-form observation, pollution search and military detection (Masoomi *et al.*, 2015). Underwater robot has been widely used in replacing humans especially in deep sea diving activities in oil and gas industry or underwater observations purpose (Anderson and Chhabra, 2002). The creation and improvement of robot fish is being researched, where it could improve efficiency and bring benefits to humans in different field.

Many fish robots have been developed (Razif *et al.*, 2014). Among the pioneers is the RoboTuna. It was developed at MIT in 1994 (Masoomi *et al.*, 2015, Yu *et al.*, 2014, Zhou *et al.*, 2008). The challenges to overcome in developing the underwater robot fish are the improvement of efficiency in swimming and performance. These what attract the researchers in various scientific realms to do research in this field (Masoomi *et al.*, 2015). Besides, robotic fish could act as a real fish underwater, where it could perform underwater observations purposes without disturbing nature. Fishes or other aquatic animals would not swim away from the robot fish (Rus and Tolley, 2015).

Most of the robot fishes developed are limited by technology and expensive. This hinders the usage of robot fish to be employed widely in various field. The number of researches on the development of underwater robot is on the increase, thus the skills and knowledge are growing. The used of cheaper material with easy control methods will lead to the increased in efficiency and performance of robot fish.

1.2 Problem Statement

The application of knowledge learned from nature has led to the advancement of biomimetic system especially in the robotic field. In the field of aquatic robot, fish can teach us human how to swim underwater efficiently. Different species of fish swim differently. However, basic mechanism of swimming has been found to be similar such as the use of tail stroke for lateral propulsion. Therefore, for the development of an aquatic robotic necessitate the investigation of live fish locomotion since it's manoeuvrability and efficiency is excellent.

Biomimetic study requires observation from nature. In the development of robot fish, one is required to study fish swimming mechanism. From there, visualization of flow around a swimming fish for measurement should be conducted under to study the effect of fish locomotion.

Most fishes generate most of the thrust using its tail. Hence, the design of the mechanical fish tail should meet the requirement and mimics the body structure of the fish body. Even though the secret of how fish swims have been revealed, there is still a lot to be learned since the field is quite new. From the literature study performed, it was found that work on Gourami fish locomotion is still lacking.

Hence, here come to the problem statements of the work where:

i. How does gourami fish propel itself?

ii. What are the characteristic of flow around gourami fish in forward motion?

iii. How to replicate the kinematic of gourami fish tail?

1.3 Objectives

In this project, the primary goal is to develop a Gourami fish tail mechanism. The mechanical fish tail developed is based on the concept of the locomotion of swimming gourami fish. The design of the mechanical fish tail mimics the motion of the tail structure of the Gourami fish tail. The mechanical tail should function in a similar manner as real fish.

The work requires the study of fish kinematics and flow visualization of Gourami fish to be experimentally performed. Hence, the secondary goal for the project will be the characterizations flow around the selected Gold and Opaline Gourami fishes obtained. The experiments were conducted in the water channel developed specifically for this work. In the channel, the fish was encouraged to swim freely in the test section while PIV measurements were performed. The data obtained will provide a valuable insight for the development of mechanical fish tail.

Once the mechanical fish tail has been developed, it was put to the test. The undulating motion of the tail in the water channel in the free stream flow were recorded via PIV system. This is to ensure the reliability of experiment, where the successful of manufactured mechanical fish tail will be evaluated. The test evaluates the similarity and functionality of the mechanical fish tail developed in comparison with the Gourami fish tail.

Objectives of the work is:

i. To capture the gourami tail kinematic and characterizing the wake of the fish tail experimentally.
ii. Developed the mechanical fish tail using the data obtained.

iii. Evaluates the developed mechanical fish tail in terms of kinematics and wake characteristics.

1.4 Research approach and scopes

In this research, the species of fish selected is a type of Gourami. Two fishes were acquired to undergo kinematic study and wake flow measurement behind the fish tail. The fish are Gold and Opaline Gourami as shown in Figure 1.1. The experiment for flow visualization of the fishes will be conducted in the water channel, where the fishes are encouraged to swim freely in the test section. Flow measurement to characterise wake shedding behind the fish tail will employed the PIV approach.

The reason for choosing the Gold and Opaline Gourami fish as test subject is because it has excellence swimming performance. Besides, the fish is highly sustainable in fluctuated environment and can thrive in poor quality water. They are recommended for beginner aquarist and suitable for experiment which switches environment between water tank and water channel. Their growth will stop around 6 inches (15cm) of dimension. Gourami is also widely available in the market.

Figure 1.1: Opaline Gourami (left) and Gold Gourami fish (right)

The experiment requires a water channel for the fish to swim in and where measurement could be performed. A water channel is designed using CATIA software and fabricated specifically for the experiments. The water channel consisting of PVC pipes, valves and water pump were assembled for circulation of the water. Variable water flow speeds were piped into the water channel. The water channel was built on top of a table rack equipped with roller for easy relocation. The test section for the experiment measured 155 x 300 x 155 mm. The PIV measurement window was around 160 x 110 mm. An example of PIV set-up is shown in Figure 1.2.

Design of the mechanical fish tail that is similar in shape with the Gourami fish was also done using the CATIA software. The mechanical fish tail was fabricated from thin elastic plastic sheet. The tail was scaled up, so the high-fidelity measurement could be performed. The ratio remains where the length of the body and tail of mechanical fish was 150mm length with 80mm of wide. Arduino Uno microcontroller is used to control the wavy motion of the fish tail. The motion is provided by the analog servo motor. The mechanical fish tail flapped inside the constant water speed at different flapping amplitudes.

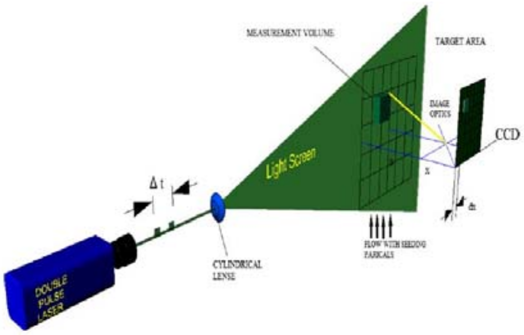


Figure 1.2: PIV experimental set-up (Babu *et al.*, 2016)

1.5 Thesis outline

Chapter 2 covers the literature review performed for this work. Basic theory and previous studies on fish locomotion and fish robot were reviewed. The subsections include flow field measurement of fishes, researches on mechanical fish and Particle Image Velocimetry (PIV). The theory of locomotion of fish, manufacturing of mechanical fish and PIV were also discussed in the background theory.

Chapter 3 covers the methodology employed in this work. The flow of the work is described in detail. It describes the design, fabrication and experimental setup. The materials, apparatus or device used is also described in this chapter. This chapter also explains how the experiment was conducted that includes challenges and difficulties faced during the fabrication of water channel and mechanical fish tail.

Chapter 4 presents the results of the experiments along with the analysis and discussions. The kinematic measurement and wake characterisation of Gold and Opaline Gourami fish, along with the mechanical fish tail will be analysed and discussions. Discussions on the wake vortex of two fish will explained in this chapter, with the flow produced by mechanical fish tail. The comparison of the flow measurement of live fishes and mechanical fish tail will also be presented.

The last chapter is the conclusions and recommendations. Chapter 5 concludes the finding from this research work. Limitation of the experiment work will be presented, Future work and the recommendations to enhance and continue the research will be entailed.

CHAPTER 2

LITERATURE REVIEW

2.1 Theory

It is a known fact that fish sheds vortices in their wake. The vortex is known as the Karman vortex street is produced by fish when the fish is swimming forward in the water. Therefore, to study flow around a swimming fish, it is important to understand vortices. The best reference about fish vortices can be found in a work published by Rosen in 1959. Before understanding the production of vortices, the theory of mechanism for fish swimming are more needed as intro for water flow surrounding the fish.

2.1.1 Mechanism involved in fish swimming

Water is important to act as a medium of its incompressibility and high density for swimming fish to generate the thrust. The density of water is 800 times compared to air, which sufficiently close to the body of fish to counterbalance the force of gravity. The water could develop a great variety of swimming propulsor including the aquatic animals, as weight support is not a primary importance (Sfakiotakis *et al.*, 1999a).

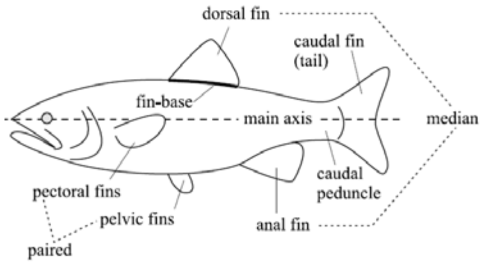


Figure 2.1: Parts of fish which function in swimming and thrust generator (Sfakiotakis *et al.*, 1999a)

The skin between the fish and boundary layer of water will result in friction drag. The friction drag will produce the large velocity gradient of the viscosity water in areas of flow. The pressure formed in pushing water aside for the fish to pass, which the drag has formed. The energy lost in the vortices formed by caudal and pectoral fins as they generate lift or thrust (vortex or induced drag) (Sfakiotakis *et al.*, 1999a).

The weight, buoyancy and hydrodynamic lift in vertical direction with the thrust and resistance in the horizontal direction are the forces that acting on a swimming fish. The Figure 2.2 could show the position of forces acting on the fish. For the supplement buoyancy and balance of the vertical forces, many fishes achieve this by continually swimming with their pectoral fins extended to avoid sinking (Sfakiotakis *et al.*, 1999a).

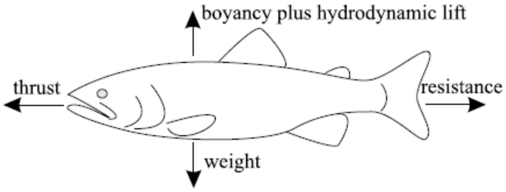


Figure 2.2: The forces acting on a swimming fish adapted from (Magnuson, 1978)

2.1.2 Production of vortices

The way of vortices produced will be further explained despite there is no formula to explain how the vortices manifested. The following explanation referred to Figure 2.2, where the frames of swimming fish are captured at intervals of 0.02 seconds (Rosen, 1959).

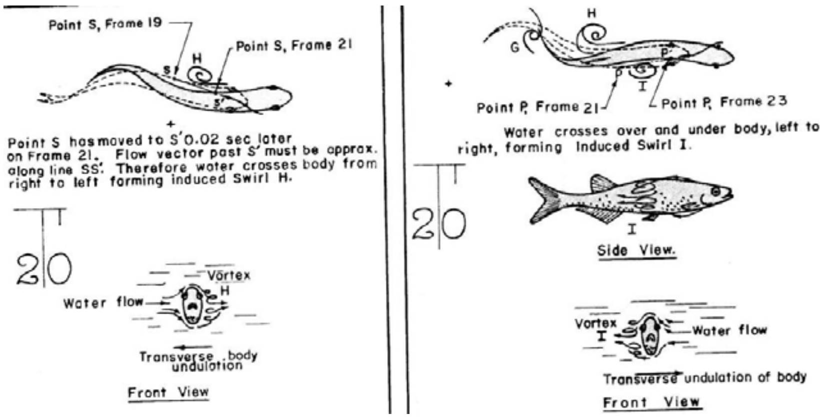


Figure 2.3: Schematic diagram of front and top view where exact tracing from photograph (Rosen, 1959)

The point S is selected at the Frame 19 (top left) and 21, which two points are connected to assume an approximate motion of the water flow. This shows that the particle is not moving respectively with the ground. In additional, the direction of S and S point shows that the path for twisting-forward motion of the fish. This indicates that the front part of the fish body is forcing the fluid particles to flow cross its body on both sides (Rosen, 1959).

The water is an incompressible fluid, hence any movement of the fish across the water will set the water surrounding its body in the motion (Sfakiotakis *et al.*, 1999a). Hence, the double vortices are formed at the downstream of fish's body. Vortex I will produce as the water is passing through the Point P created the by the reversed cross-flow. Side view of the fish illustrates the water path when the fish body is moving side to side in an undulating motion with twisting head (Rosen, 1959).

2.1.3 Idealized vortex pattern (Karman Vortex Street)

The vortices shown in Figure 2.4 shows a series of vortices generated by the fish tail. The fish is assumed to swim in a straight line from left to right. A series of "circular pattern" will be left behind on the swimming path (Rosen, 1959).

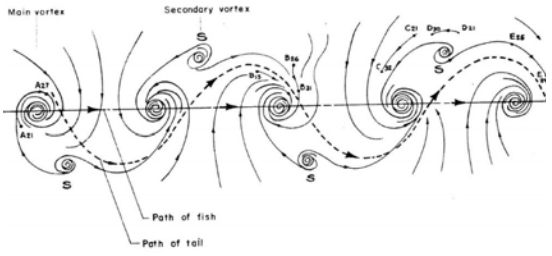


Figure 2.4: Idealized vortex pattern of fish when swimming (Rosen, 1959)

The wake behind the fish consist of a series of strong counter-rotating vortices, where the structure will link into a chain (Nauen and Lauder, 2002). Four vortices are observed in the frontal plane, which two produced during the downstroke of the fin, and the two produced during the upstroke (Drucker and Lauder, 2000). The structure of the wake is of a thrust-type, which a jet of high velocity flow was formed with reversed rational direction of vortices (Drucker and Lauder, 2000, Sfakiotakis *et al.*, 1999a).

Besides, Lighthill and Videler prove that the reversed Karman street results exclusively from the tail movements (Lighthill, 1969, Videler, 1993). The wake structure which the vortices produced had been investigated that behind oscillating foils that were not attached to a body (Anderson *et al.*, 1998).

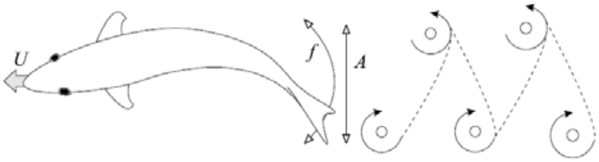


Figure 2.5: The wake of swimming fish associated with thrust generation has reverse rotational direction (Sfakiotakis *et al.*, 1999a)

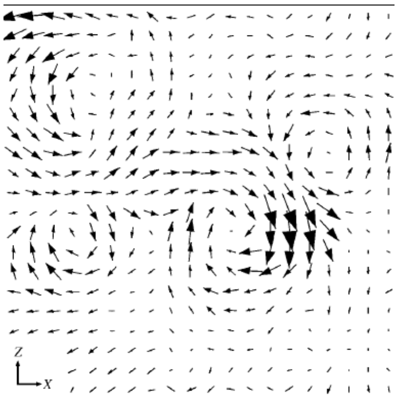
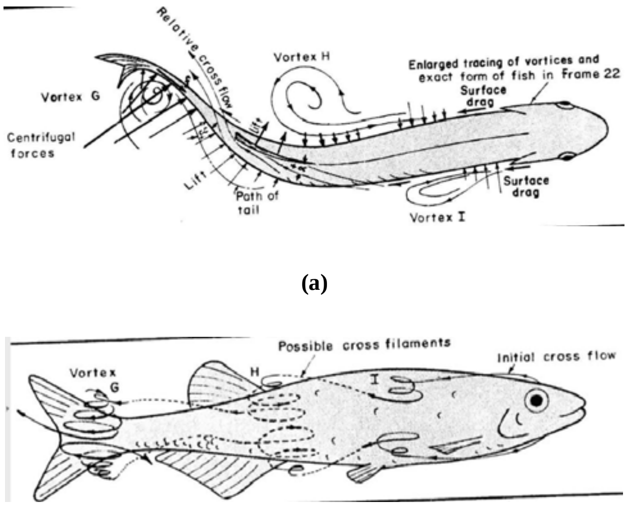


Figure 2.6: Water velocity vector field in perpendicular from the pectoral fin from PIV measurement (Drucker and Lauder, 2000)

2.1.4 Structure of vortex

The structure of vortex is divided into three main type as shown in Figure 2.3(a). The image was a duplicate of frame 21**.** There are three vortices in Figure 2.3(a). Vortex I represent a newly created vortex, while vortex H is a fully developed, energetic vortex. Vortex G is a matured vortex located at the tail of the fish.

Normally the placement of the vortices with respect to the fish body and tail located at upstream and downstream position. Vortices will be produced after the cross-flow filaments as shown in Figure 2.3(b). 'Vortex necklace' or 'vortex chain' will be created when the filament of the cross-flow and mid-body exist at the same time (Rosen, 1959).



(a)

(b)

Figure 2.7: Side view of vortices of fish for connected vortex necklace system (Rosen, 1959)

The undulating pump mechanism which will generating the vortex wake was first proposed by Blinckhan *et al* (Blickhan *et al.*, 1992). Müller *et al* supported that an "undulating pump" mechanism, whereby these zones nearby swimming fish create a circulating flow around the inflection points of the body (Müller et al., 1997).

The discrete vortices are formed and shed in the wake when the circulating flow propagates along the body and interacts with the bound vortices created by tail movement upon reaching the caudal fin (tail) (Sfakiotakis *et al.*, 1999a).

The similar mechanism is proven by Triantafyllou and Triantafyllou, where the mean of recapturing energy and reducing the apparent drag of swimming by at least half of the whole energy (Barrett *et al.*, 1996, Triantafyllou and Triantafyllou, 1995).

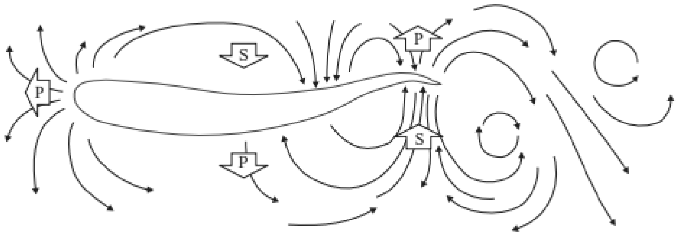


Figure 2.8: The flow field around the body of swimming fish, as P and S corresponding to pressure and suction zone which form the basis of "undulating pump" mechanism (Müller *et al.*, 1997)

2.1.5 Evolution of vortex

All vortices manifest, grow and develop, before gradually disappear with respect to of time. The changes will evolve with time, where the sequence of evolution will be manifestation, development, expansion, final expansion and quieting. These sequences are briefly illustrated in Figure 2.9. There are 4 stages that starts from a to d.

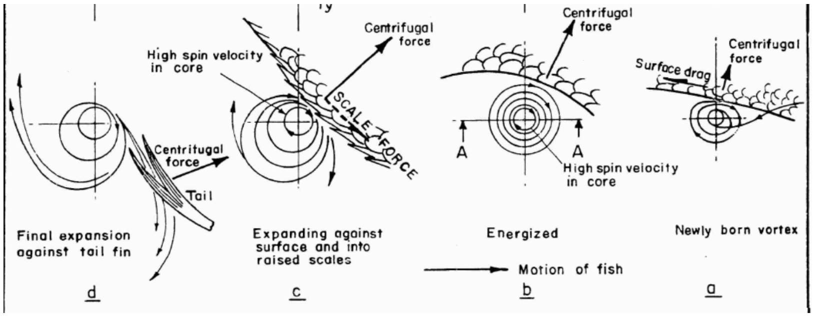


Figure 2.9: Pressure and forces of the fish vortex as a function of age (Rosen, 1959)

Vortices are born when the head of fish is twisting during swimming. Thus, the fish body crosses over the water flow and small initial energy will be produced. The vortices produced will be developed when the fish continues to swim forward which creates drag on the surrounding fluid. The dragged fluid will produce more energy thus more vortices develop in the same direction. Then, the vortices expand where the substantial centrifugal pressure exerts against the fins and body of the fish. Vortices glides around the fish in its curved path as the fish is moving (Rosen, 1959).

In the final expansion, the vortex will lose the energy to expands against the tail where it envelops and swipes but no too far from its core. At a certain angle, the pressure at the tail will produce a forward thrust due to the vortex. The quieting stage come last when the double vortices are shed from the side-to-side motion of the fish tail. The pressure of the vortices decreases after shedding occurred. larger part of its kinetic energy has been spent. The velocity of water particle is quite low where the vortices left the tail. This represent the energy that has been expended by the fish to propel itself forward.

2.2 Previous Studies

2.2.1 Research on flow field measurement of fishes

Research on the flow field measurement with body movement of live fish using Stereo PIV has been performed by Sakakibara and colleagues (Sakakibara *et al.*, 2004). Lighthill predicted the propulsive efficiency of fish locomotion, together with Wu which observed the three-dimensional fish-like mode based on slender body (Sakakibara *et al.*, 2004, Sheu and Chen, 2007). The slender body theory can be applied to calculate the velocity vectors of the fish when swimming in a very low Re (Reynolds number).

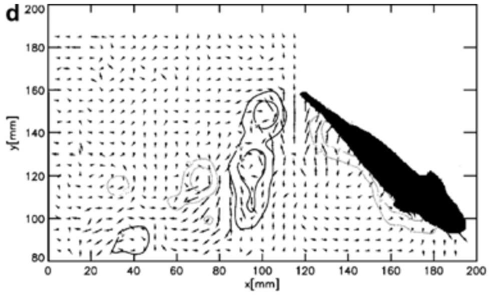


Figure 2.10: Example of velocity vectors around a turning fish (Sakakibara *et al.*, 2004)

Wolfgang and colleagues realized that the vortex shedding is generated when the fish is swimming in a straight line and turning (Wolfgang, 1999). The flow around the fish revealed that the vortex shedding when the fish manoeuvres (Sakakibara *et al.*, 2004, Sayeed-Bin-Asad *et al.*, 2016). The vortex shedding could be viewed in a clearer way during the turning motion of the living fish (Sakakibara *et al.*, 2004). Hesselink in 1988 mentioned that the sub-image correlation (SCPIV) is used when high seeding densities were allowed, and the maximum particle displacement was of the order of a few times the particle diameter (Hesselink, 1988). This method was not being suggested into this experiment as the conditions are not suitable to ours. This is because the vectors will be missing in high velocities and blurring by the moving swimming appendages (Stamhuis and Videler, 1995). Hence, the vectors near around the fish could not be detected.

According to Liao in 2007, turbulence may be considered as a feature of the hydrodynamic environment that is a benefit rather than a constraint (Liao, 2007). The research done by Breder in 1965, Weihs in 1976, Sutterlin and Eaddy in 1975, Webb in 1998, Hinch and Rand in 2000, Smith in 2003 concluded that the fish could reduce the locomotion by exploited towards the turbulence flow (Liao, 2007, Breder, 1956, Hinch and Rand, 2000, Smith, 2003, Sutterlin and Waddy, 1975, Webb, 1998, Weihs, 1973).

The study of fish motion and its resulting wake with viscous effect have also been analysed using computational methods. Incompressible Naiver-Strokes equations has been employed in such study (Sheu and Chen, 2007). The resulting flow field was analysed to further refine the robotic fish locomotion mechanism. Tony and Chen observed that the location and size of two vortices which are regularly generated at both sides of the fish body change with the velocity of fish when it moves forward. So, the data of vortex shedding could be recorded at time interval of 0.05s or even smaller when the fish swim in streamline (Sheu and Chen, 2007). This method could detect the changes of vortex shedding at each interval of time effectively when the fish is moving.

The fish required to swim freely in the test section (Sakakibara *et al.*, 2004, Sayeed-Bin-Asad *et al.*, 2016). Hence, the fish can swim without any distraction and the natural pattern flow of the fish could be captured. Furthermore, the fish required to swim near to the center of the test section (Drucker and Lauder, 1999). Regarding to the research, the minimum allowance distance for fish's pectoral fin between any wall was 50mm. This is to avoid the hydrodynamic "wall effects" by Webb 1993, which could ensure the data of unimpeded flow structure resulting directly from movement of pectoral fins could captured (Drucker and Lauder, 1999, Webb, 1993).

Besides, training is being introduced to enhance the result of the experiment data. The habitation of the fish in flow tank is required before performing the experiment (Stamhuis *et al.*, 2002). Training may approach from introduce the fish in water-still water and exposure under the LED of PIV. The flow pattern of the fish tail could easy captured under still-water or low speed of water, where the flow is laminar and velocity does not change suddenly in time or space (Stamhuis *et al.*, 2002).

2.2.2 Research on mechanical fish

Nowadays the development of the biomimetic robot fish has been a hotspot (Zhou *et al.*, 2008). The first mechanical fish, RoboTuna, was built at MIT in 1994 (Masoomi *et al.*, 2015, Yu *et al.*, 2014, Zhou *et al.*, 2008). A model based on elongate-body theory was built by Lighthill in 1960 and 1970 to analyse the carangiform propulsive mechanism (Lighthill, 1960, Lighthill, 1970). Then, Wu in 1961 has developed a two-dimensional (2-D) waving plate theory where the elastic plate used as fishes (Wu, 1961). The theoretical and experimental studies have explored the possibility of applying the propulsive mechanism of fishes for aquatic vehicles *(*Zhou *et al.*, 2008).

The basic idea on most of the mechanical fish is taken from the design of the Tuna Fish due to its streamline with compressed body shape. Besides, the Tuna Fish are capable of swimming freely at high speed during reproduction period. The compressed body shape enables fish to generate less drag and more flexible for turning and manoeuvring (Masoomi *et al.*, 2015, Rus and Tolley, 2015). Rus and Tolley mention that the soft robots promise to be able to bend and twist with high curvatures and this can be used in confined space to deform their bodies in a continuous way and thus achieve motions that emulate biology. The study of caterpillar led to the soft robotic system (Rus and Tolley, 2015). The soft material could provide an opportunity to bridge the gap between the machines and people, which could be increasing their potential for interaction with humans (Rus and Tolley, 2015). The disadvantages of the soft body will be challenging in control as it is too flexible and bending.

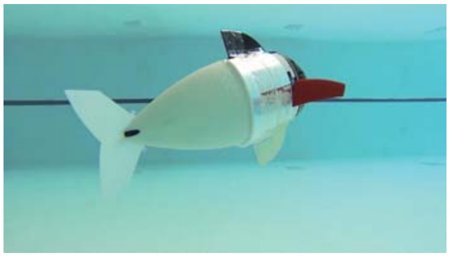


Figure 2.11: Prototype of soft-body robot fish (Rus and Tolley, 2015)

Mechanical fish is designed to move forward. Hence, there are many designs could be act as reference, which based on locomotion and parts of fish. The tail structure could be done in wave curve shape with necessary tail parameters including the tail fin shape, relative wavelength, number of joints, length of joints and the position of every joint (Zhou *et al.*, 2008). The caudal fin, which act as the tail, is created in high aspect ratio concept (Masoomi *et al.*, 2015, Yu *et al.*, 2014). Pectoral fins, which could produce the suitable thrust and propulsion, play the main role for mechanical fish to swim forward. Basically, the three servo actuators of the pectoral fins will be controlled by three motors for locomotion (Zhou *et al.*, 2008). The pelvic fins are needed for propulsion, steering and paddling to achieve the balancing of the fish (Yu *et al.*, 2014).

For controlling the depth and forwarding motion of the mechanical fish, system of creating the buoyancy could aid it. Fluid elastomer actuator with centre channel and gear pump will be inserted in the mechanical fish which act for buoyancy producing (Katzschmann *et al.*, 2014, Masoomi *et al.*, 2015, Rus and Tolley, 2015). The resting and actuated state of the mechanical fish is controlled by the water and air with the aid of volume and pressure control (Rus and Tolley, 2015). Controlling the speed of the gear pump determines the volumetric flow from one side of the fin to the other side, hence produce the forwarding movement of mechanical fish (Katzschmann *et al.*, 2014).

For the fabrication, the material of the mechanical fish could be sourced from multi-material 3D printing (Rus and Tolley, 2015). The mechanical fish will be fabricated in the form of soft body with rigid head (Rus and Tolley, 2015, Yu *et al.*, 2014). The soft body of the mechanical fish could be fabricated from rubber or polydimethylsiloxane (PDMS) silicon (Masoomi *et al.*, 2015) while the rigid head could be done by Acrylonitrile-Butadiene-Styrol-Copolymers (ABS) through 3D printing (Rus and Tolley, 2015) or any suitable composite. The waterproofing issue could be solved by using epoxy resin to coat the fish body. The joints are vital for the flexible movement of the fish.

For the computational and control system, the microcontroller will be used with the servo motor for controlling and DC Motor for propulsion (Katzschmann *et al.*, 2014, Masoomi *et al.*, 2015, Rus and Tolley, 2015, Yu *et al.*, 2014, Zhou *et al.*, 2008). Microcontroller used to program the algorithm for flapping while the servo motor is used to control surfaces in turning and various movement of fish. In addition, the DC Motor will provide the propulsion or thrust for mechanical fish to swim forward. The electrical power sources of the mechanical fish need to be soft, flexible and lightweight (Rus and Tolley, 2015).

Design of wire-driven robot fish is mimic the real fish mechanism. An elastic beam is used to imitate the fish backbone, while the wires act as fish muscle. Servo motor connected with drum wheel is used to reel and unwind the wires, where the wire act as fish muscle relax and contract. Flapping motion could be done by controlling the motor rotate left and right (Li *et al.*, 2013). The experiment is performed where the robot fish is swimming in C-motion and S-motion to compare the effectiveness of mechanical fish swimming (Liao *et al.*, 2014).

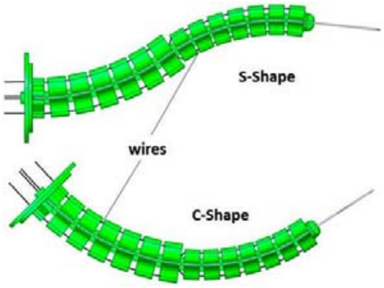


Figure 2.12: Motion modes of S and C shapes (Liao *et al*., 2014)

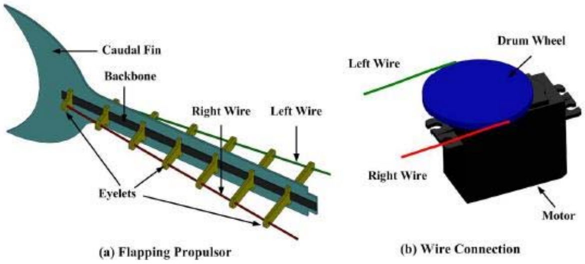


Figure 2.13: Wire-driven flapping propulsor design (Li *et al*., 2013)

2.3 Experimental Studies

2.3.1 Water channel design

Existence of water tunnel is used to flow visualizations where the experiment is harder control and undergoes in wind tunnel. The idea of fabricating a low-cost water tunnel for educational purpose was created by M Zahari from Department of Mehanical Engineering, Curtin University. The softwares of SolidWork and AutoCAD 2012 were used to design the water tunnel. A rectangle glass tank with 0.001m thickness was used to design as water tunnel. Glass material is used for its high durability and transparent in surface. The flow guide is made of two clear PVC with radius of 17cm. While for the pup and piping system, PVC pipes with a submersible pump is designed. The pump designed to minimize the problems where risk of leakage, pump cavitation etc (Zahari and Dol, 2015).

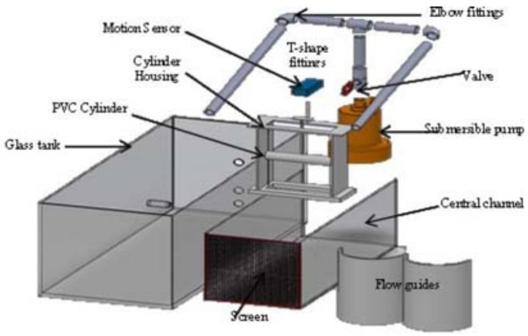


Figure 2.14: Exploded view of water tunnel (Zahari and Dol, 2015)

From the 2nd International Conference on Advances in Mechanical Engineering and its Interdisciplinary Areas (ICAMEI-2015) which the paper written by Department of Mechanical Engineering, Vidyavardhini's College of Engg. & Tech., University of Mumbai, the design of water channel is following the most common configuration of pattern. The pattern of design is connected into three modules, where are inlet module, test section and outlet module. Solid Works using as the software for design (Kalyankar *et al.*, 2015).

For the test section, the length designed not to be too long for avoid the large thickness of boundary layer. Hence, the dimension of WHL: (0.1 X 0.15 X 0.7) m is designed in rectangular shape. For inlet module design, the inlet plenum exists for receiving the water from piping system towards convergent section. Inlet plenum functions to get the suitable delivery point from piping system while convergent section used to reduce the turbulence damping performance. Baffle exist for safety factor, where covering the inlet delivery point. For outlet module is connecting the whole setting of the piping system (Kalyankar *et al.*, 2015).

Figure 2.15: Actual assembly of water tunnel (Kalyankar *et al.*, 2015)

2.3.2 Particle Image Velocimetry (PIV)

Particle Image Velocimetry appeared 25 years ago where since now has become an essential measurement tool in fluid mechanics laboratories. The main function of the PIV where act as a tool for flow visualization, no matter in non-reacting or reacting flows. Besides, the major asset of the PIV techniques is to deliver a quantitative and instantaneous measurement of velocity over a whole plane simultaneously. Then, the 2D flow structure in become available in both visualization and quantification together with computing tools (Brossard *et al.*, 2009).

The PIV are divided into several categories, but for the most common categories will be two-component PIV (2D2C) and stereo-PIV (2D3C) (Brossard *et al.*, 2009). Standard 2D2C PIV is used to measure two components velocity in one plane with one camera while 2D3C PIV is used to measure three components velocity in one plane with two cameras. 2D2C PIV will be used in common as the experimental setup for 2D3C PIV more expensive and complicacy (Sayeed-Bin-Asad *et al.*, 2016).

The pattern of the fluid is traced by seeding particles to get the entire velocity field of the given area measurement. The laser light will have scattered by particles and recorded into two separate frames on Coupled charged devices (CCD) Camera sensor. The time interval between the two laser is given and the image magnification obtained from camera calibration. Hence, the projection of the local flow velocity vector onto the plane of the light sheet will be obtained (Brossard *et al.*, 2009).

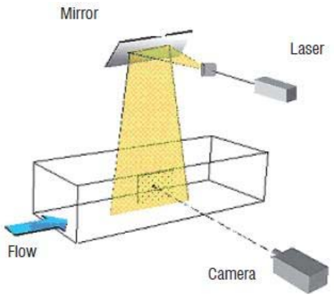


Figure 2.16: Schematic Diagram of typical PIV Setup (Brossard *et al.*, 2009)

For the seeding particles, most of the experiment desire to have the particles be non-toxic, non-corrosive, non-abrasive, non-volatile and chemically inert. Compare to gas flow, the seeding particles have frequent use in liquid flow. From the analysis of A Melling, the particles in these experiments were chosen to have nearly neutral density for the experiment fluid. Thus, the adequate tracking responses could still be expected. Besides, the accuracy of the velocity field depends on seeding particles capability to follow the instantaneous movement of the uninterrupted phase (Melling, 1997).