Biomimetic Study of Hydrodynamic Analysis of Flapping Fish

Author

Ossama Hafeez

Registration Number

00000318998

Supervisor

Dr. Emad Uddin

SCHOOL OF MECHANICAL & MANUFACTURING ENGINEERING

NATIONAL UNIVERSITY OF SCIENCES AND TECHNOLOGY

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Author

Ossama Hafeez

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Thesis Supervisor:

Dr. Emad Uddin

Thesis Supervisor's Signature: ____

SCHOOL OF MECHANICAL & MANUFACTURING ENGINEERING

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Abstract

The need to depend on ocean is increasing day by day and hence to cope with the demand one must be advance in the field of bio-mimics to fully understand its ideology. The world of Bio-Mimics has deeper roots in the robotic field hence the development and innovation of unmanned underwater vehicles diversely adopts the benefits of locomotion and maneuverability over conventional designs. The purpose of our research is to study hydrodynamics of flapping tuna fish at different flow regime's & 2-D wake vortices analysis is performed of flapping Tuna fish placed in various real life configurations inside water tunnel, to better understand their hydrodynamic performance, reverse Von Karman vortices generation and shedding and their effect on desired configuration, followed by the two 3D printed Tuna fish mold filled with flexible silicone to ensure the flexibility and fatigue resilience, with individual variable frequency control flapping mechanism. The designed mechanical flapping fish undergo flow visualization with PIV (Particle Image Velocimetry) setup. Experiment is carried out in flowing water of (0.055-0.1) m/s with Tail flapping amplitude of 40^0 degrees. The objective is to study the hydrodynamic efficiency of single fish & two fish in side-by-side configuration to better understand the fluid dynamics associated with it & to apply that concept in future to create efficient propulsion system. Hydrodynamic efficiency for single fish case is found to be 58% while in side-by-side configuration it's 54% for synchronous mode of locomotion while for asynchronous it is 31%. The mission of bio-mimics is to create a world of engineering design inspired from the nature itself due to its various benefits over conventional human designs. Thus, by taking another step closer to eco-friendly propulsion system & waste reduction.

Key Words: *Hydrodynamics, Wake Vortices Analysis, Particle Image Velocimetry, Mechanical Flapping Mechanism, Reverse Von Karman Vortices.*

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CHAPTER 1: INTRODUCTION

The research work carried out in this thesis is based on experimentation by using PIV (Particle Image Velocimetry) setup, two separate mechanical flapping Tuna fish placed in various real-life orientations to observe the vortices generation and shedding and their effect on each other. Experimentation has been carried out in water tunnel with transparent test section for camera to observe and translate the motion of particles around flexible body of Tuna fish.

1.1 Background, Scope and Motivation

For the past 12 to 15 years a lot of research has been carried out in the field of bio-mimics, ranging from water to air, and then air to space, in order to determine best and optimal hydrodynamic design and energy harvesting methods via mechanical fins and eels, the purpose of these researches is to explore the fluid dynamic world of wake structure analysis, vortex shedding, formation of leading and trailing edge vortices & aerodynamic/hydrodynamic characteristics, to make a structure with better design and better energy harvesting methods or better flapping propulsion systems. These designs are then deployed in air, space & marine environment to have better result by sustaining harsh environmental conditions. More has been explored in domain of fish's kinematics, respective fins, and their movement, is monitored very closely with real fish to determine the efficiency of their fins and how different fins interact with each other in various real-life maneuvering conditions. To solve the mystery of designed locomotion issue with real fish, researchers begin to develop new ways to study their behavior by mimicking their motion through robotic fish to study the hydrodynamics associated with certain design [1]. But each experimentation has its own benefits and drawbacks. Our proposed model includes the use of individual mechanical flapping system which mimics the motion of Tuna fish includes the use of motors, gears & rack with silicone casted fish mounted on one end of rotating rod. PIV setup is used to study Tuna hydrodynamics.

Figure 1: Bullet Train Bio-mimics [25]

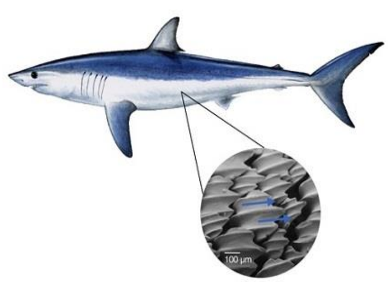


Figure 2: Shark Skin Bio-mimics [25]

Figure3: Velcro Bio-mimics [25]

Examples of bio-mimics from daily life includes the designing of famous bullet train on the basis of beak shape of bird, swimmers' suits are designed on inspiration of shark skin and its v shape scales having best hydrodynamic advantage hence face less drag as compared to normal suits having greater drag induced due to FSI (Fluid-Solid Interaction), another example is of plant bonding which gave birth to Velcro. Bio-mimics is the nature inspired designs having advantage over conventional human designs because nature test them in harsh environment, and they survive that is the reason they've better efficiency over human designs.

1.1.1 Forces acting on Fish

Since fish locomotion is related to the medium water, its important characteristics of incompressibility and high density are related to fish, such that any small perturbations caused by the motion of fins in a localized movement causes disturbance in surroundings since water is 800 times denser than air but equals to the body of marine animals such that it counterbalances the effect of force on fish. Since movement is due to fins so the force required for propulsion is produced by the movement of either short or long based fins. Fins dimensions normal to the flow are called span and those parallel to the water flow are called as chord.

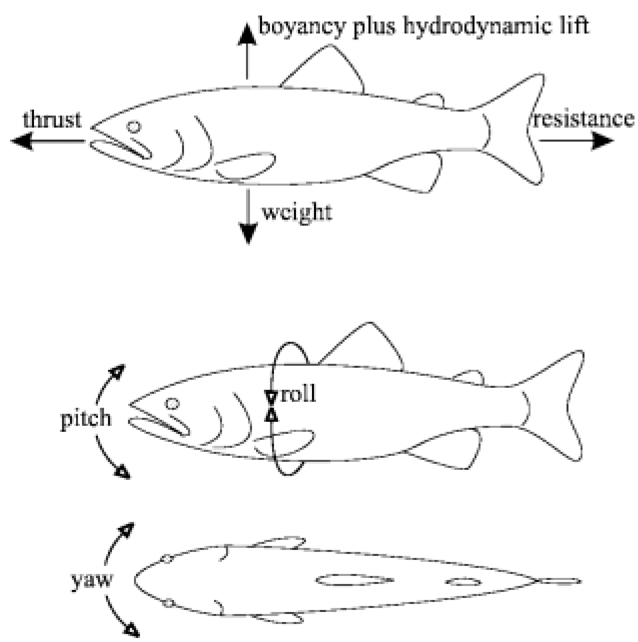


Figure 4: Forces Acting on Fish [29]

While drag are of two types namely,

1. **Viscous or Friction Drag**:

   It's mainly due to the friction between the surface of fish and boundary layer created by water. It arises as viscosity increases in areas of water flow, where large velocity gradient exists. It depends on the wet area, speed of fish & boundary layer effect in fluid flow.

2. **Vortex or Induced Drag:**

   Drag is due the movement of fish, when it pushes water aside by moving specific set of muscle it faces the force of water in the form of drag which mainly depends on the shape of fins, also energy lost due to the generation of vortex by fins also tends to have drag effect on fish.

1.1.2 Swimming Locomotion

Fish locomotion is characterized as swimming and non-swimming. Non- swimming includes jumping, flying, gliding, jet propulsion and burrowing whereas swimming locomotion is classified as periodic and transient.

1. **Periodic Swimming**

   Also called as steady state swimming, this type is characterized by the cyclic repetition of propulsive movements, this technique or motion is developed by fish to travel long distances at constant speeds.

2. **Transient Swimming**

   Called as unsteady swimming, its due to the rapid movement, maneuvers & turns, it is employed for avoiding predators and catching preys and it lasts only milliseconds.

1.2 Fish Fin's & Locomotion

Fish moves due to the movement of fins, and their movement is associated with one another to produce certain kind of motions, fish locomotion is a result of force exerted by fins, against surrounding layers of water. Such motion is attained by contraction of muscles by fish on either side of the body to generate waves that travels across its body, starting from nose and ending on tail, slightly getting bigger as they move across and approaches tail. The vector forces acting on water layers cancel out latterly by generating a net force in backwards which in turns act as a source for fish locomotion. Different fish have different fins ranging from pectoral to caudal fins. There are two kind of motion exercise by fish, Body/Caudal Fin (BCF) locomotion & Median/ Paired Fin (MPF) locomotion. 85% of the fish belongs to BCF locomotion families. Fish eligibility to move efficiently and effectively is due to their body shape, fins formations and kinematics followed by certain motion. The streamline body of fish allows it to experience less drag and reduces turbulent flow, while thrust is produced by kinematics for movement, thus different fish have different advantages such as Tuna can swim at high speed with efficient maneuverability, which allows the fish to be a better predator among his class, in the same way dolphins can swim steadily with little thrust at constant speeds, combing both of their abilities in Bio-mimics we can translate their motion to be used in ships travelling from continent to continent. Thus, fish locomotion is the motivation for the progress & advancement in the field of marine vessels, propulsion system.

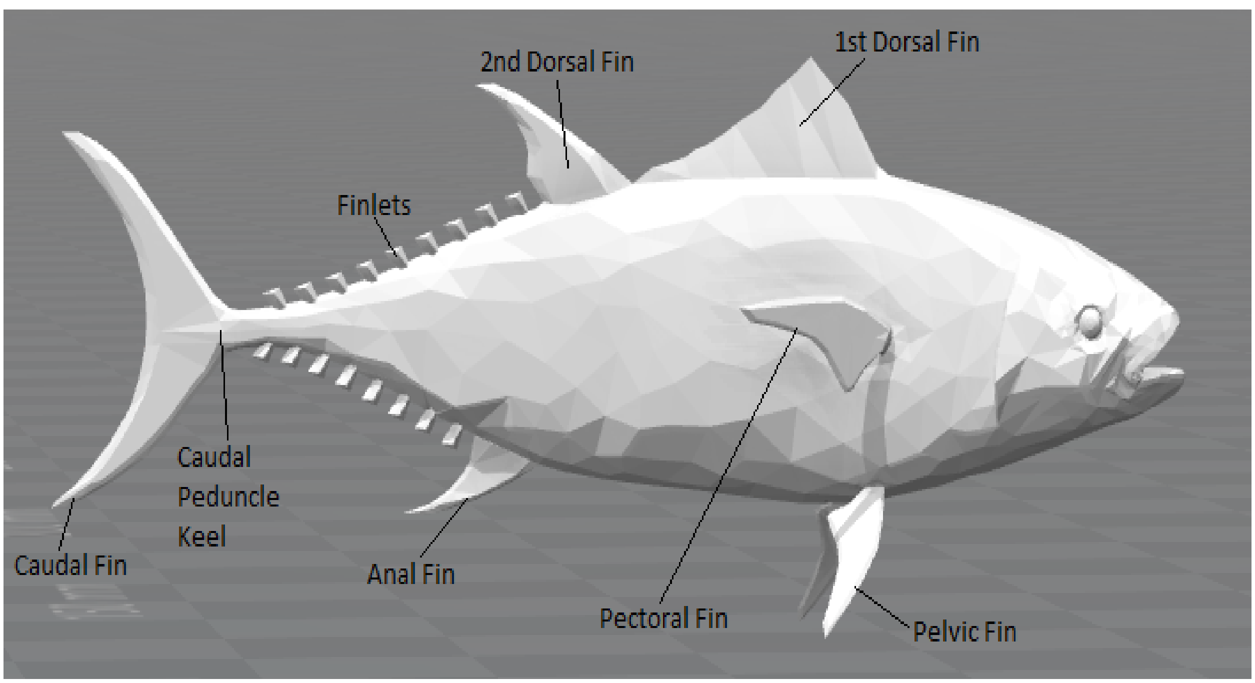


Figure 5: Tuna Fish Fins Anatomy

1.3 Swimming Propulsions

Two kinds of propulsions are seen by fishes, one is BCF propulsion and MPF propulsion. Tuna fish belongs to the category of BCF propulsion in which two modes of swimming lies one is undulation and second is oscillations, Tuna undergoes undulations mode of swimming, in which transient and periodic swimming leading to acceleration and cruising. Since Tuna is a predator so when it wants to catch its prey, it accelerated and when it moves in the form of school to cover larger distances it uses cruising mode of locomotion.

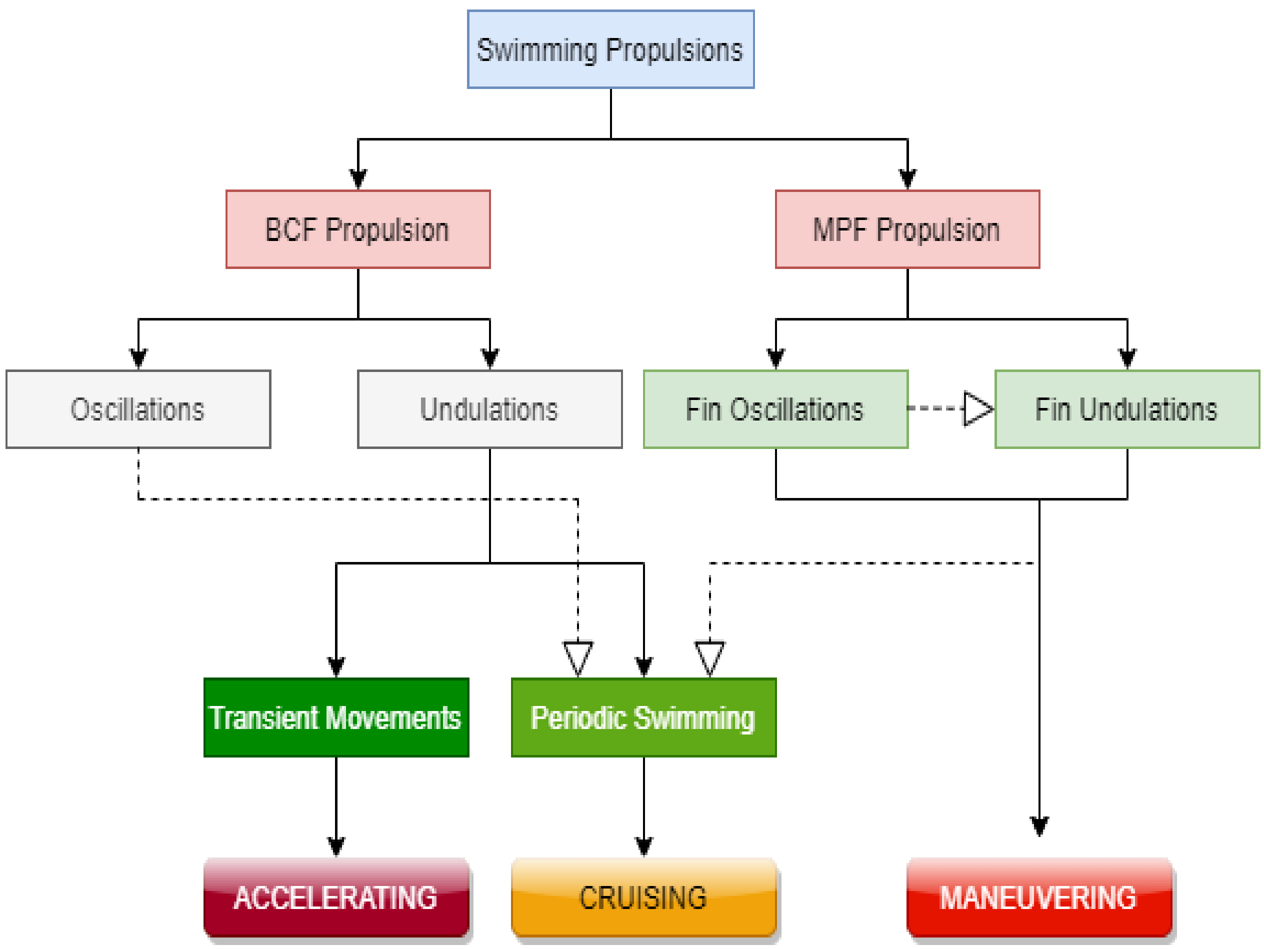


Figure 6: Flowchart of Fish Locomotion Types [7]

1.4 Body/Caudal Fin Locomotion

Most of the fish swims by producing undulatory waves that travels across the body and reached caudal fin, which in turns is the force required for locomotion. This type of locomotion is termed as Body/Caudal Fin locomotion (BCF), swimming using these body structures mainly includes anguilliform, sub-carangiform, carangiform, and thunniform locomotory modes, as well as the oscillatory ostraciiform mode. BCF is most efficient locomotion and have higher cruising speeds maintained for prolonged periods.

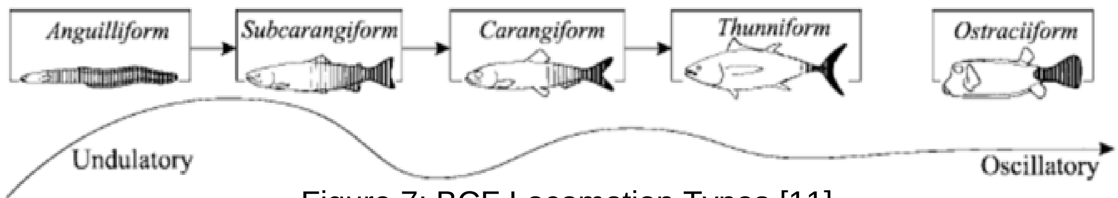


Figure 7: BCF Locomotion Types [11]

A. Anguilliform

B. Sub-carangiform

C. Carangiform

D. Thunniform

E. Ostraciiform

1.4.1 Anguilliform

Large whole body amplitude is seen in anguilliform mode of swimmers, moreover during undulation one complete propulsive wavelength is seen along the fish body. Fish belongs to this mode can swim forward or backwards depending upon the direction of propulsive wave [30].

1.4.2 Subcarangiform

This type of mode is quite similar to anguilliform fish mode but with the exception of fluttering is limited anteriorly thus by increasing in half of the fish posterior [30].

1.4.3 Carangiform

This type of mode is even faster than anguilliform and subcarangiform by restricting its undulation to thirds of its body due to which this locomotion mode has the ability to turn and accelerate. These characteristics are due to the rigidity of the body [30].

1.4.4 Thunniform

This type of locomotion is highest speed among its class of BCF locomotion. Thunniform uses lift based mechanism for thrust, this mode comes with a drawback of not being efficient on turning and acceleration at low speed [30].

1.4.5 Ostraciiform

Ostraciiform locomotion is based on oscillatory mode, in which caudal fin of ostraciiform flap like pendulum while body remains stationery [30].

1.5 Median/Pair Fin Locomotion

In this type of swimming locomotion median fin and paired fin uses a set of muscles to control the movement of fins in order to move and rotate. Two types of fish locomotion is seen using a set of median and/or paired fins to produce flapping motion that is based on lift base propulsion while the other one is rowing which is drag based to produce thrust which is required for swimming. MPF locomotion has advantage of higher maneuverability. Paired fins consists of pectoral and pelvic fins, while Median fins consists of dorsal, caudal, anal and adipose fins. MPF locomotion is divided into 7 categories as follow.

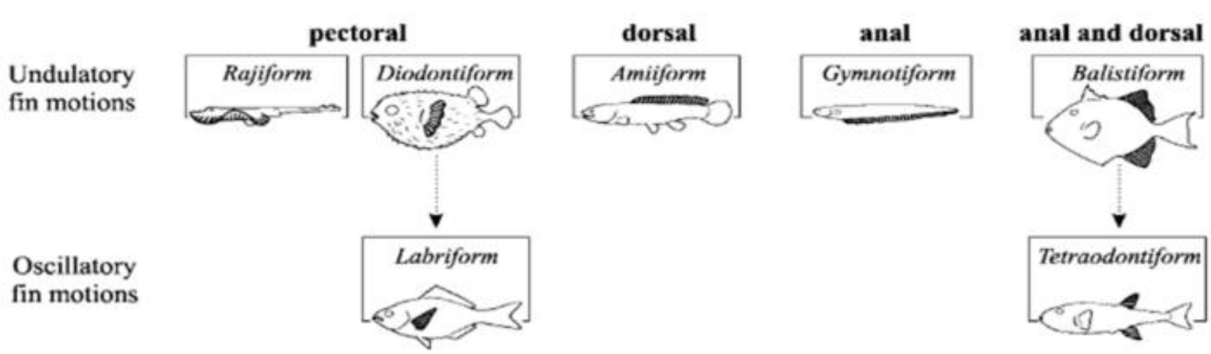


Figure 8: MPF Locomotion Types [11]

A. Rajiform
B. Diodoniform
C. Labriform
D. Amiiform
E. Gymnotiform
F. Balistiform
G. Tetraodontiform

1.5.1 Rajiform

These swimmers have a special characteristic of having a large, flexible, and triangular pectoral fin. Rajiform swimmers flap their fins up and down in such way that they propel by changing fluttering/undulating amplitude ranging from anterior fins to posterior fin [30].

1.5.2 Diodoniform

This type of swimmers aren’t much different than the prior ones, propulsion is same by flap of fins up and down, undulating propulsion is same passing down to the large pectoral fin [30].

1.5.3 Amiiform

These types of swimmers have very long special fin but placement of that fin is other than the mentioned above. Amiiform locomotion uses dorsal fins for propulsion by keeping their body rigid [30].

1.5.4 Gymnotiform

Gymnotiform swimmers are just like Amiiform, both have a very special long fin except it uses anal fin instead of dorsal, swims by keeping their body stationery [30].

1.5.5 Labriform

These swimmers locomote by only using pectoral fins, rest is all same as mentioned above except it belongs to the category of oscillatory motion just like pendulum [30].

1.5.6 Tetraodontiform

Locomotion is same as labriform except these swimmers uses combination of dorsal and anal fins for the purpose of propulsion. This type also belongs to oscillatory propulsion instead of undulatory [30].

1.6 Tuna Fish

Tuna is a saltwater fish residing in the tribe of Thunniform. They are known for their rapid maneuverability and high speed over long distances at constant speed reaching up to 47 mph. Tuna is active, agile predator having a sleek, streamline body allowing the fish to swim at high speed with less drag due to its hydrodynamic advantages of the design and fins configurations is used in marine environment efficiently and effectively to design better hydro character unmanned underwater robots to overcome the risk probability associated with unreachable man missions underwater. With the advancement in UUV's, it's easier than ever to explore deep ocean water horizon to study and discover what lies beneath us and how to use that hydrodynamic knowledge for the betterment of humanity. Yellowfin tuna is top of the charts with best hydrodynamic advantages with their length ranges from 1.5m to 2.4m & fins from pectoral to caudal with small finlets providing effective and efficient locomotion.

Figure 9: Yellow Fin Tuna Fish [28]

1.6.1 Hydrodynamic Analysis

In order to study the vortices generated by fish for propulsion we are using experimental technique called PIV particle image velocimetry. Different fish have different abilities and characteristics on the basis of their fins and locomotion mode, in order to adapt the concept of bio-mimics (nature inspired design) we have to study the fluid dynamics associated with the movement of fish under water called as hydrodynamic analysis. In order to study the vortices, we have replicated the motion of scaled down, silicone casted tuna fish on the basis of Streamline chart and Reynolds number.

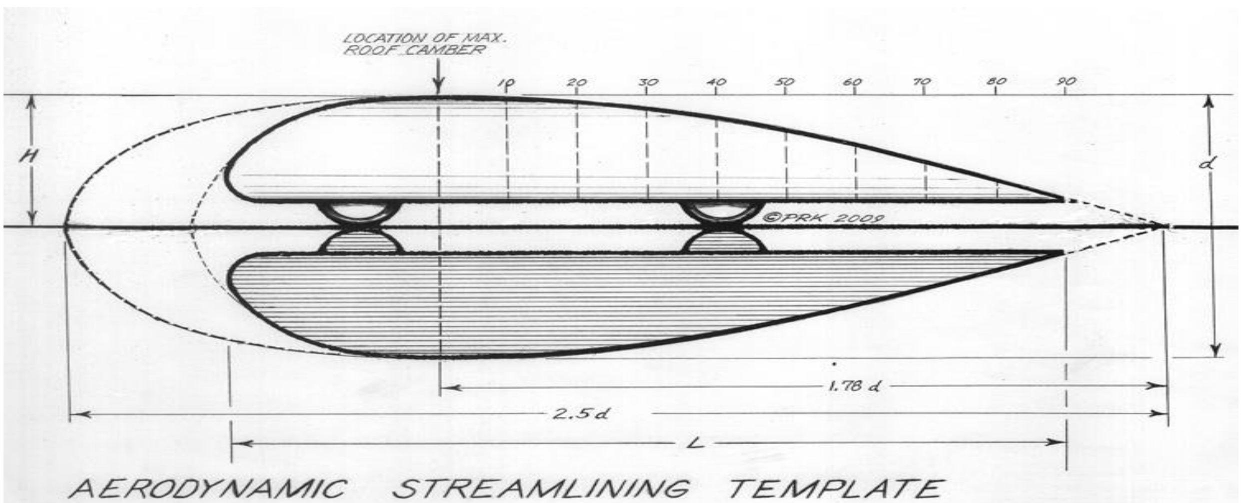


Figure 10: Streamline Chart [13]

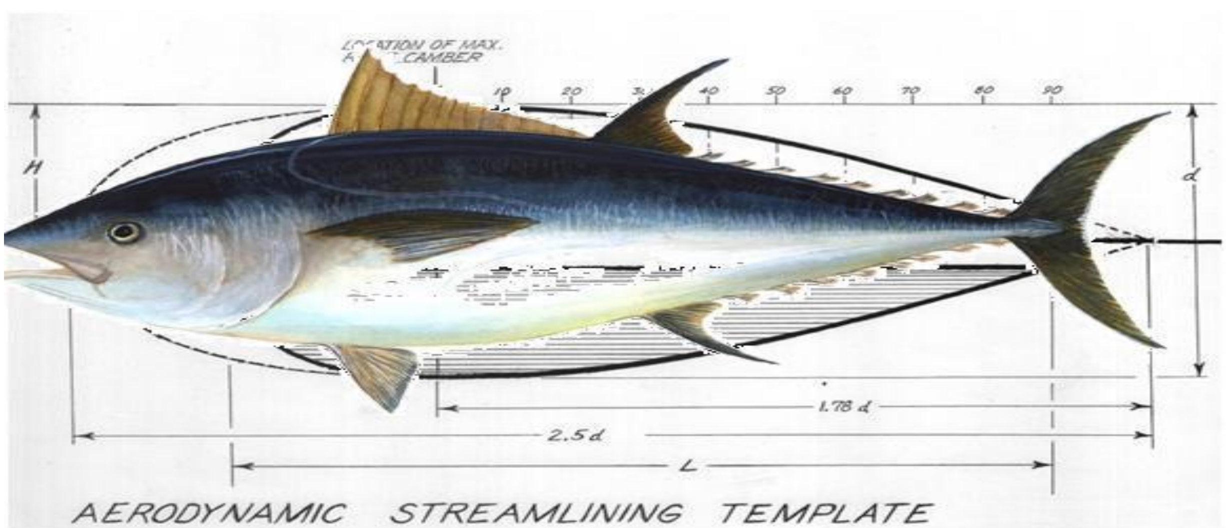


Figure 11: Tuna Fish in Template [13]

1.6.2 Dimensional Analysis

Based on streamline chart, we take length of the fish is approximately 2.5 times of the height of caudal fin. Also, this scale down technique is supported via Reynolds number balancing in experimental and real life sea conditions. The length of the object is 120mm thus height of caudal fin is 49mm and width is 28.25mm.

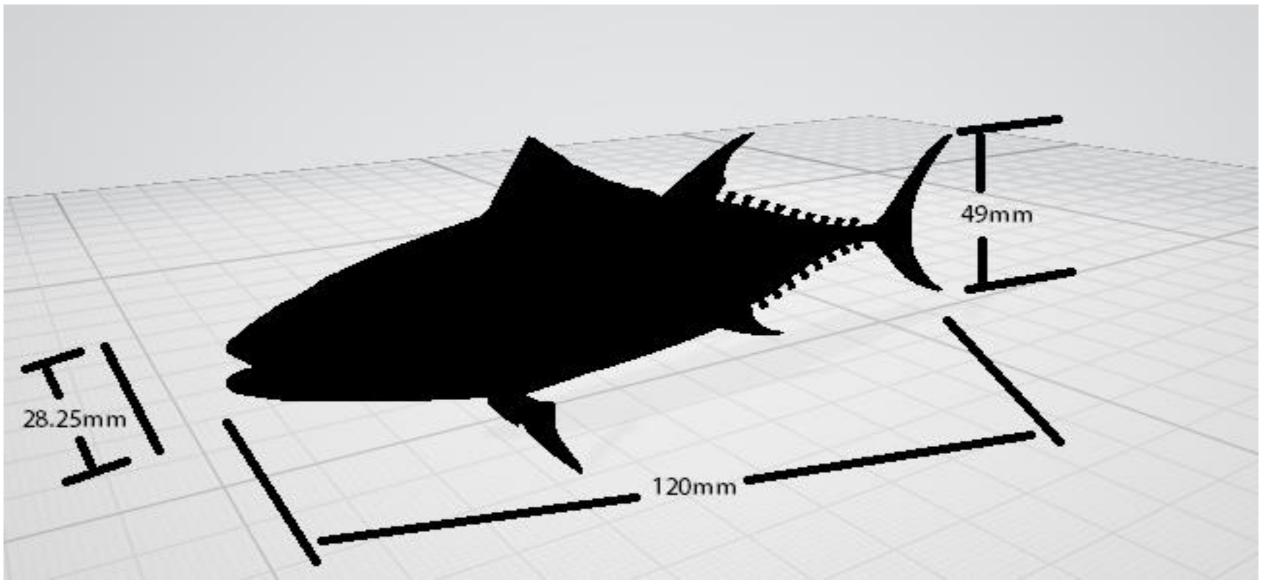


Figure 12: Tuna Fish Dimensions

Table for Correlation of Experimental & Real-life Reynolds Number

Table 1: Reynolds Number Correlation

Experimental Reynolds Number	**Real Reynolds Number**
Re=$V * \frac{L}{v}$	**Re=**$V * \frac{L}{v}$
V=0.055-0.1 m/s	**V=0.0508-0.508 m/s**
L=120mm	**L=1100-2100mm**
v= **1.0533**$* 10^{-06} \frac{m^2}{s}$	v= **1.0035**$* 10^{-06} \frac{m^2}{s}$
Re≅6200	**Re≅6200**

The scale down model is validated via Reynolds number and a correlation is made between experimental and real-life conditions and found to be equal.

1.7 Reverse Von Karmen Vortices

Reverse von Karman vortices are generated by flapping foils/fishes in which the thrust is pointed away from body thus propels the body in upstream direction. These vortices are repeating swirling vortices produced by flapping because of vortex shedding and it is responsible for the un-steady flow separation from blunt geometries [31].

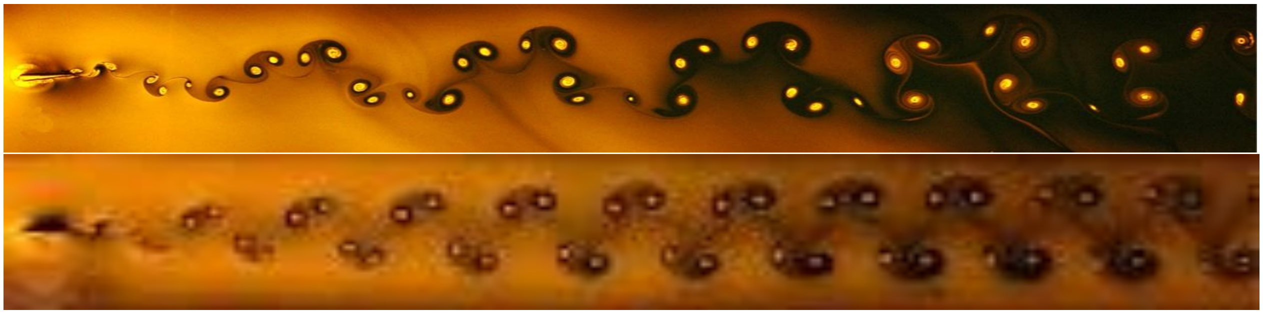


Figure 13: Flapping Foil Reverse Von Karman [31]

Difference between Von Karman & Reverse Von Karman Vortices.

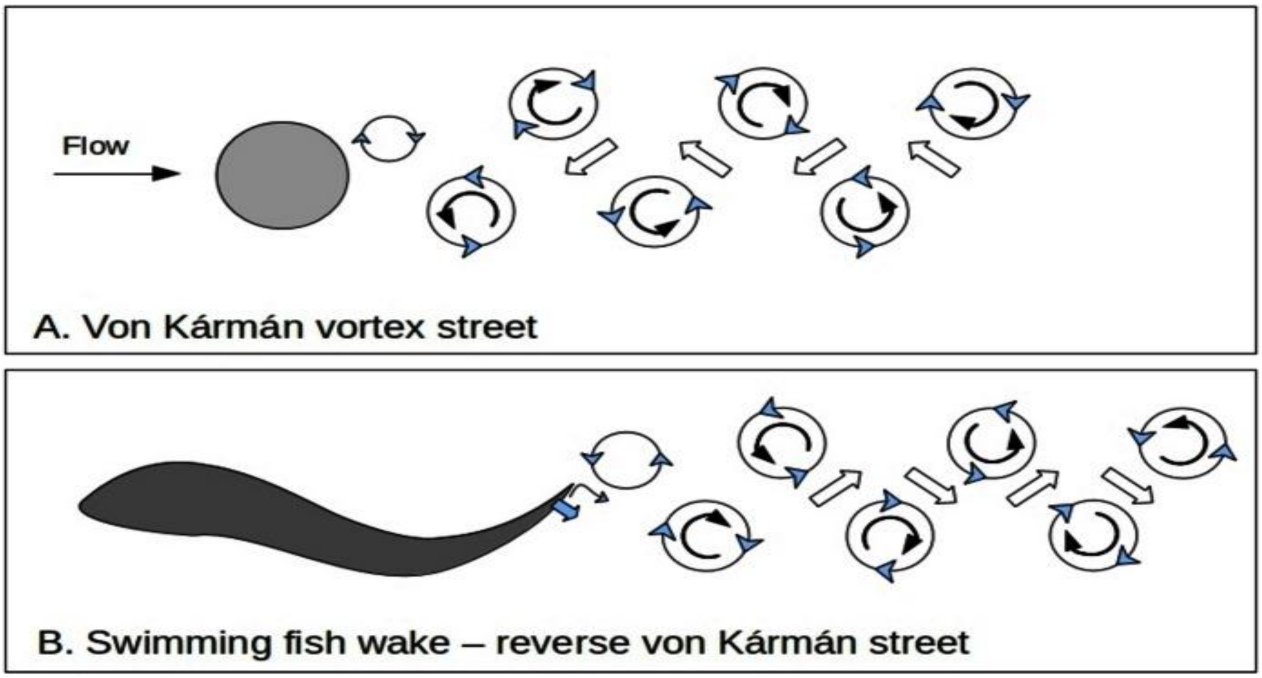


Figure 14: Difference Between Von Karman & Reverse Von Karman [26]

CHAPTER 2: LITERATURE REVIEW

Previous studies (e.g. Partridge et al. 1983), have analyze the structure of school of giant bluefin tuna via aerial view and report that the fish movement in school is very localized, they follow different patterns but most prominent is the c shape parabolic pattern followed by school of tuna [32]. M. Sfakiotakis et al. 1999 has studied the locomotion of fish swimming in detail, with detailed analysis of body/caudal fin and median/paired fin propulsion and different category of fishes lies in different tribes of fish exhibiting a special kind of motion and then the comparison is drawn with different results obtain via different sources, one example is of PIV [11]. Sakakibara et al.2004, uses stereo PIV technique to study the flow around the moving fish, to study its locomotion, three cameras are pointed at fish to capture ring vortices created around fish body in 3-Dimensional space, also did numerical study in order to compare those 2 results [1]. Marut et al.2012, uses a novel approach to fabricate jellyfish in order to find the propulsion thrust produce during contraction and relieving of the shell, both by experimentation as well as numerically using complex CFD approach, jellyfish model is fixed in chamber and by using loadcells they measure thrust force via DAQ using computer [33]. CK Hemelrijk et al. 2014, have also discussed the hydrodynamic benefits of fish swimming in school and alone in different configurations and that configuration also effect their oxygen consumption by numerically modelling different real-life scenarios to calculate drag acting on fish [34]. Mattia Gazzolaa et al. 2015, in order to find the gait and speed selection, translate the motion of fish and consider it as a strip of some thickness flapping just like mimicking the motion of fish, to calculate its tail beat frequency, muscular torque, thrust and drag acting on inertial swimmers [35]. Mohsen Daghooghi et al. 2015, studied the hydrodynamic pro's of swimming in diamond and rectangular shape patterns, did a numerical FSI (Fluid-Sloid Interaction) modelling of neutrally buoyant bodies in certain pattern till quasi-steady state reaches in order to increase swimming efficiency [36]. Chuin Lai Hoong et al. 2019 has studied the hydrodynamics of Gourami fish tail by mimicking the locomotion of gourami fish with 2mm plastic sheet out of which the tail is cut and pasted on rotating rod connected with servo motor in order to control flapping frequency and has done Digital PIV at Flow velocity of 0.2m/s and at Reynolds number of 28000 [27]. Lauder GV et al. 2019 has done experimentation with dead fish in wake of cylinder in order to observe the hydrodynamic advantages adopted by fish in school experimentation is carried out for tuna and other fishes at high tail beat frequency and explore the performance space of swimming fishes [2]. Diego Moreira et al. 2020 studied the hydrodynamics of flapping foil and have done the numerical simulation at Reynolds number of 100000 by utilizing the NACA 0012 foil profile and have calculated the hydrodynamic forces, pressure fluctuations & coefficient of drag in order to mimic the locomotion of aquatic animal [16]. Feng et al. 2020 has done kinematic study and hydrodynamic of c turn tuna like bodies and have done numerical simulations at Reynolds number of 764000 and have explain the reason behind the faster acceleration of Tuna fish, detail analysis of flapping tuna fish wake is done and discussion is drawn on the basis of hydrodynamic forces, pressure and drag like factors [8]. Lauder GV et al. 2020 has studies the hydrodynamics of yellowfin tuna fish finlets and its kinematics with real tuna fish and have done numerical simulation as well to make a correlation between results obtain from experimentation and simulations. Results are based on several factors like forces, momentum, coefficient of drag and pressure [23]. Xia Wu et al. 2020 has studied the kinematics of flapping foil and have done the experimentation on NACA 0012 at a detailed range of Reynolds number of 100-100000 [20].

CHAPTER 3: EXPERIMENTATIONAL SETUP MANUFACTURING

To make fully variable flapping mechanisms for two separate fishes we have to firstly design the concept in solid works, which translates the motion of fish in such a manner that flapping is restricted to 20^0 right and left (range pick from literature review). In order to do that we have to use some driving mechanism like electric motor and then translate its rotary motion to, to and fro motion by using cam, follower and slider technique:

3.1 Fabrication of Flapping Mechanism

Solid work design:

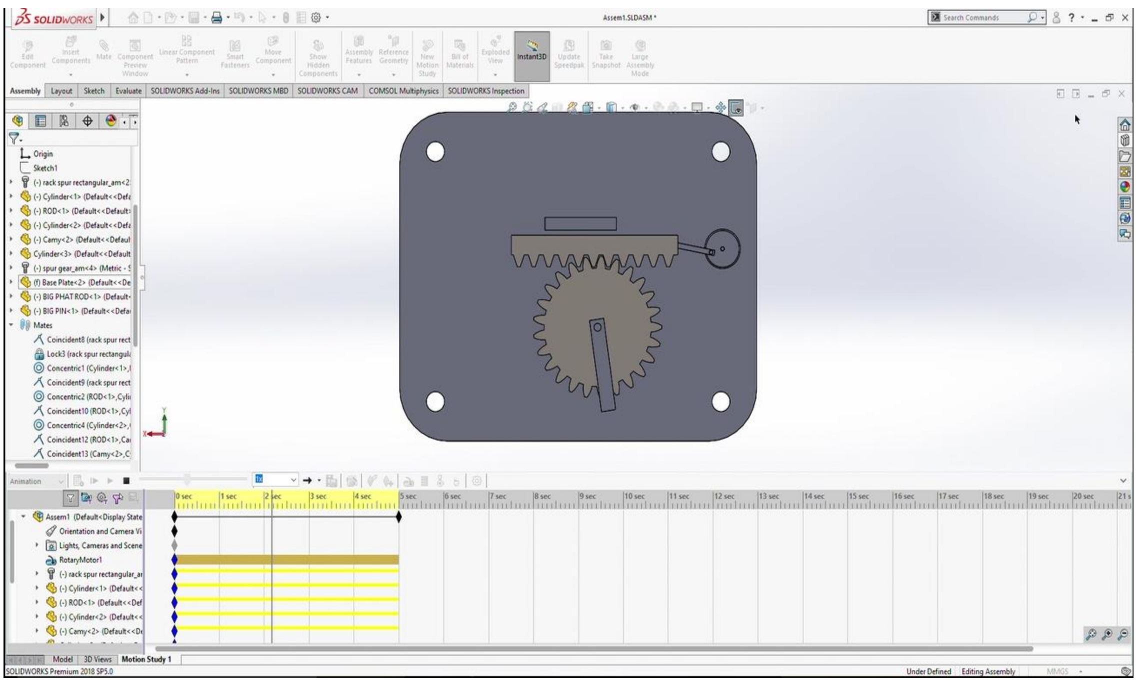


Figure 15: Solid Works Mechanism

Then we did iterations to make a reliable variable flapping frequency controller which didn’t only operate at different tail beat frequencies but also measure them via infrared sensor and Arduino microcontroller and display them on screen.

3.1.1 Development of Mechanical Flapping Fish

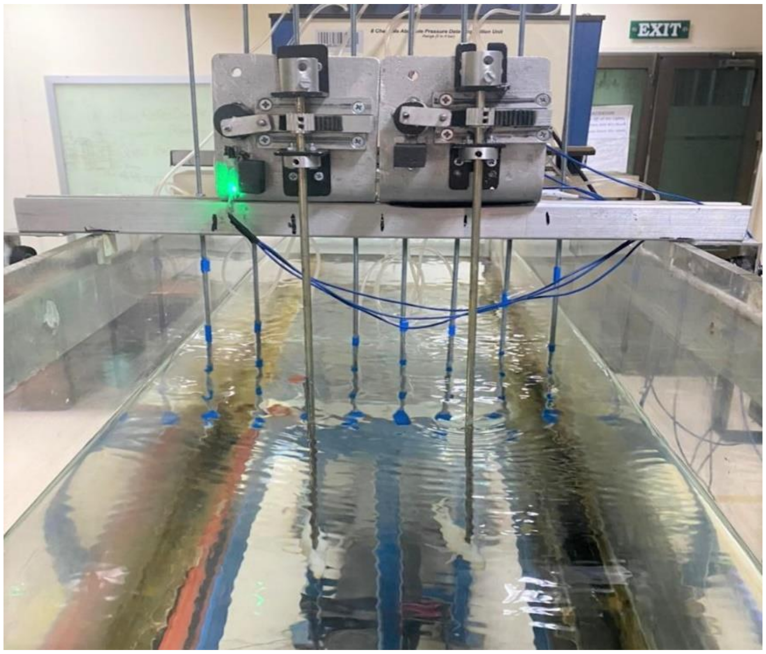


Figure 16: Fish Flapping Mechanism

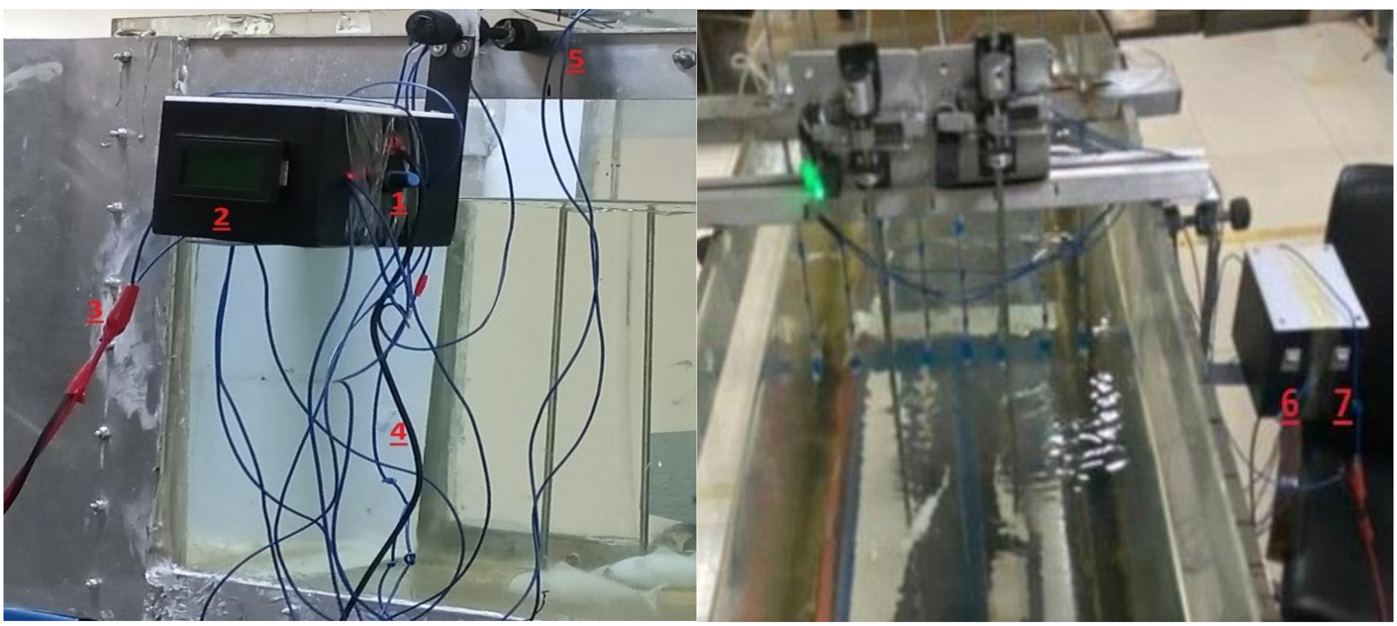


Figure 17: Variable Frequency Control DAQ

1. Variable Frequency Modulator
2. RPM Display (i.e., 1-10 Minutes & Average)
3. DAQ Power Supply 12v
4. DAQ PC Cable
5. IR Sensor Cables
6. Motor 1 Switch
7. Motor 2 Switch

3.1.2 Schematics of Fabrication of Mechanical Flapping Mechanism

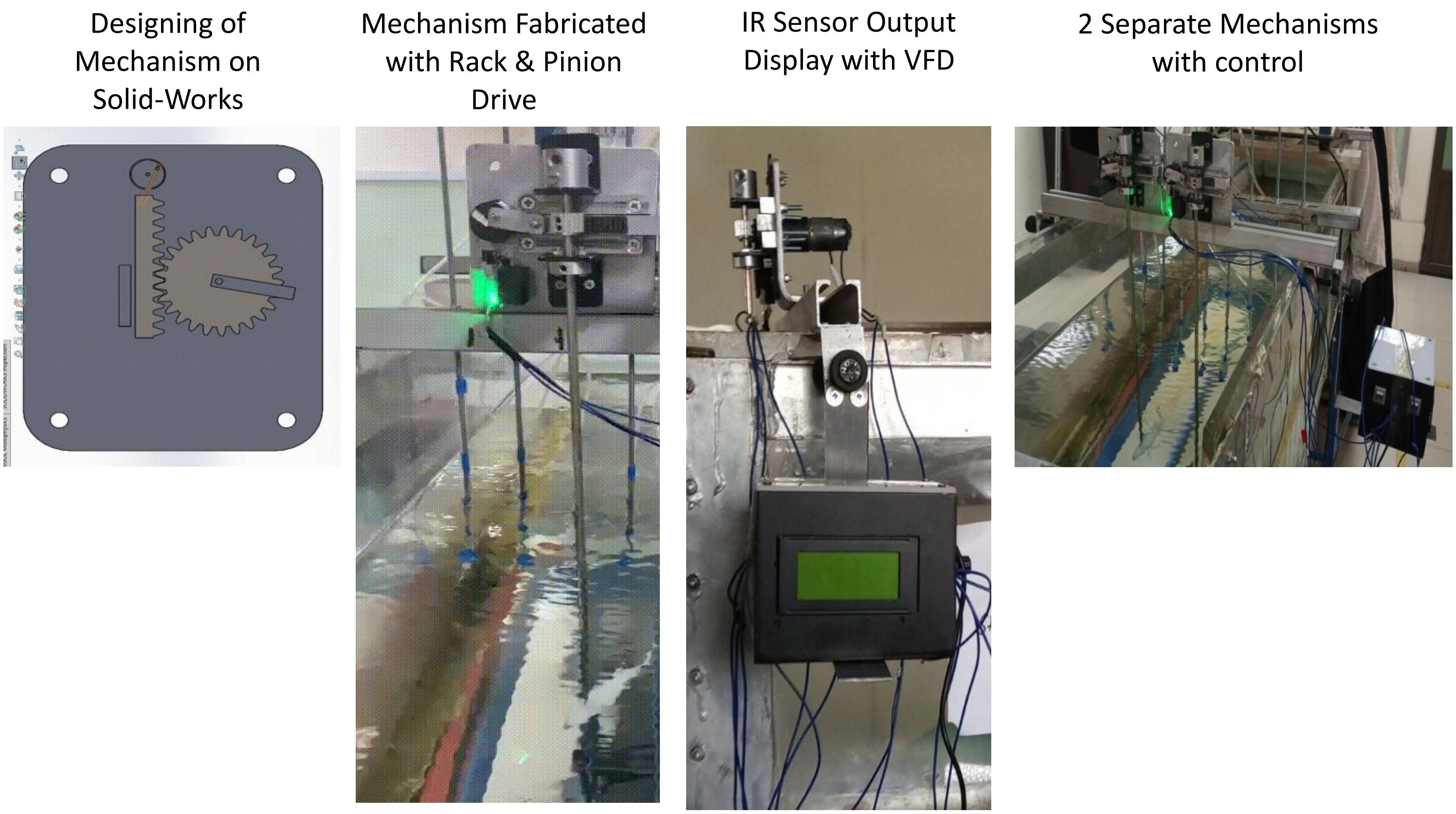


Figure 18: Fabrication Steps of Flapping Mechanism

3.2 Fabrication of Tuna Fish Via Silicone Casting

For fish manufacturing we have tried several processes ranging from 3d printing to silicone casting Every method has its own benefits over other but with drawbacks as well.

3.2.1 3-D Printing via TPU Flexible Filament

First find 3d Tuna fish cad model that can be printable, then open that file in Cura Ultimaker, divide the fish in two parts in 60-40% ratio in spinal split form then finalize the dimensions and put supports for fins, after the finalization of part generate G codes for file and then start printing. Drawback is flexibility cannot be achieved with TPU, also 3d printing still in developmental phase and hence very expensive, we can use SLA printing technique, but facility isn’t available readily.

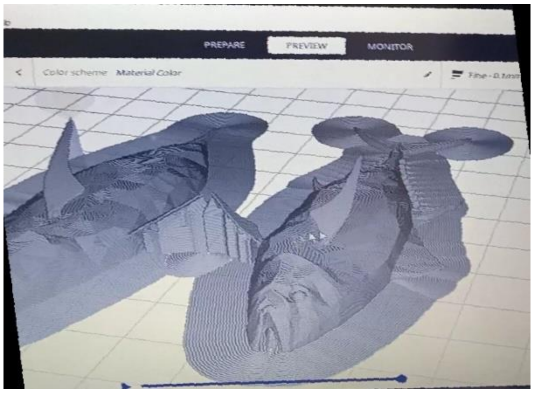


Figure19: Cura Ultimaker Fish Split

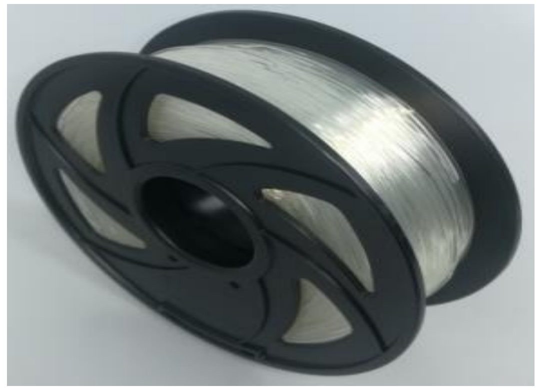


Figure 20: TPU Transparent Filament

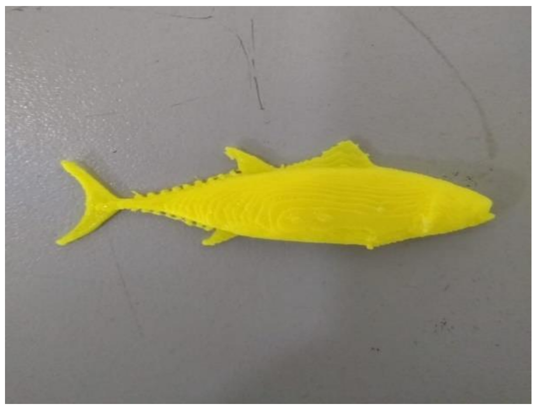


Figure 21: 3D TPU Printed Fish

3.2.2 Silicone Casting in Plaster Paris Mold

Firstly, 3d print a fish in 2 halves vertically from grills, and the attach these 2 parts together, then hold the fish in rectangular acrylic box and put Plaster of Paris in solution form slowly and let it set, solidify & then inject silicone in mold.

Drawback is tail and fins cannot be easily extracted from mold, and plaster of Paris setting time is quite small hence cannot be able to make mold easily.

Schematics of Paster Paris Mold:

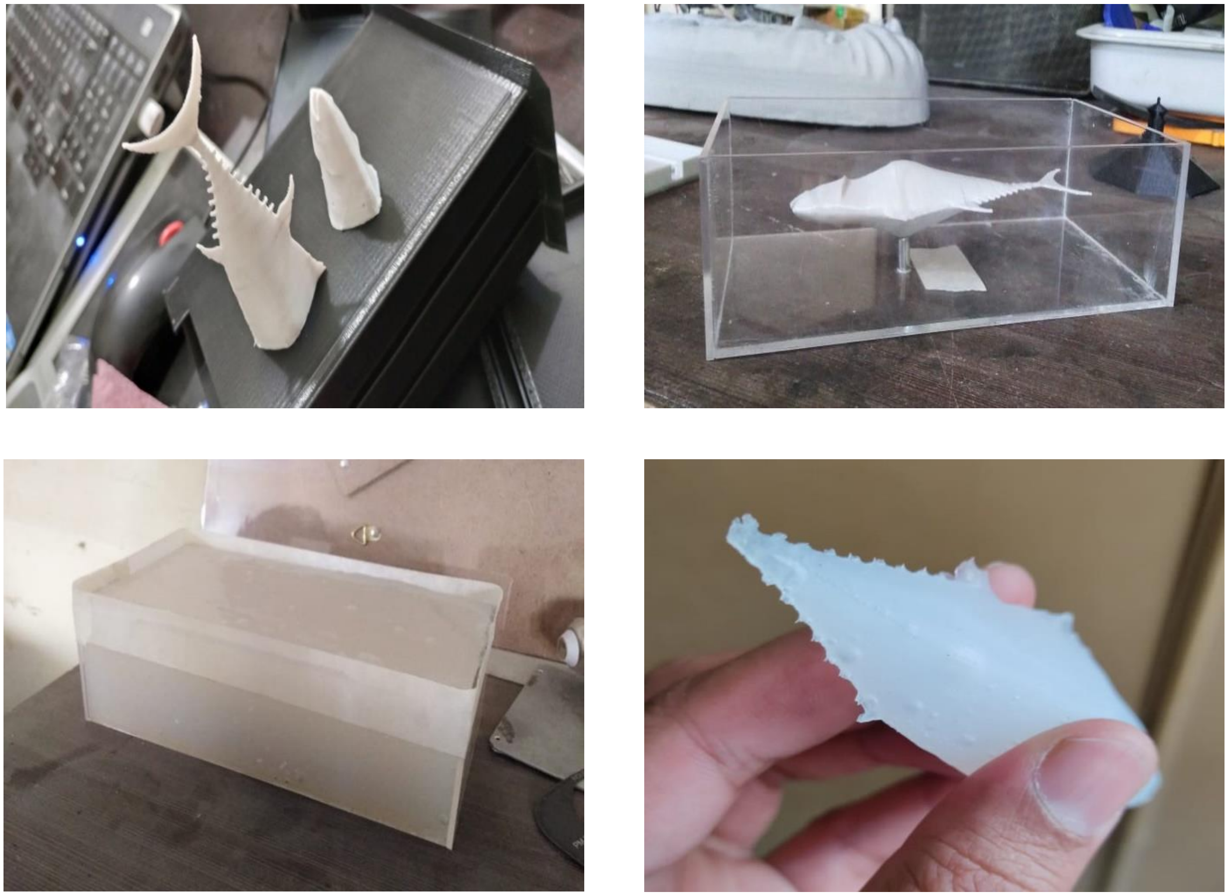


Figure 22: Fish Fabrication Via Plaster Paris Mold

3.2.3 Silicone Casting in 3D Printed Mold of Tuna Fish

Firstly, made mold using solid works mold tools module and then do a little bit of machining for inlet and outlet ports in mold leading to the pressure silicone injection. Because silicone has good flexibility and good resistance to fatigue, also it should bear the force of moving water while flapping but wings of thickness this small cannot be made in silicone casting hence polypropylene sheet of 0.5mm is used for fins.

Drawback is fins & scales still cannot be made in mold.

Schematics Of Silicone Casting:

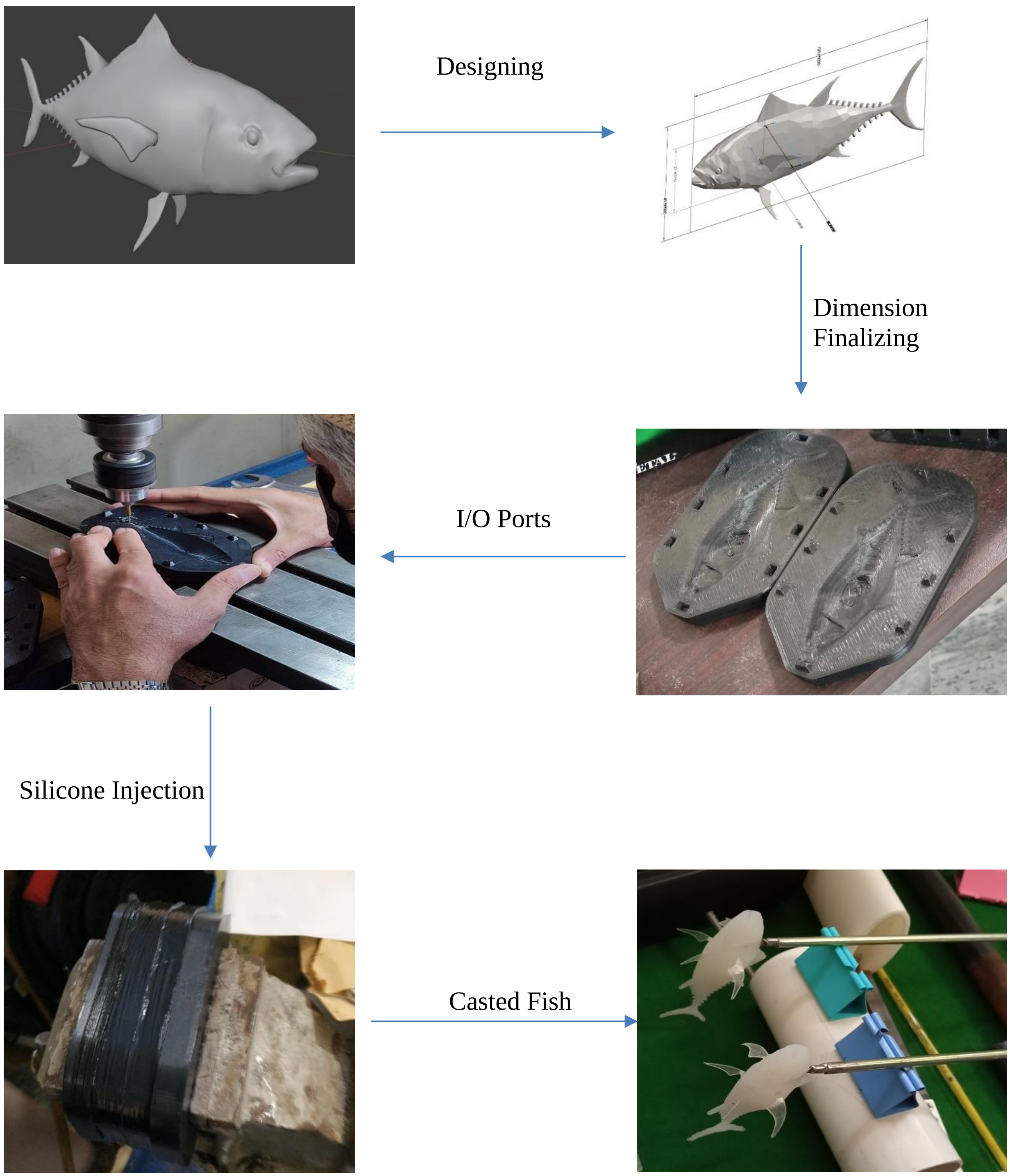


Figure 23: Fabrication Steps of Fish Via Silicone Casting

CHAPTER 4: EXPERIMENTATION

Two kinds of experimentation are carried out in this research, first is based on MATLAB video processing via Image J software, second one is based on flow visualization technique called as Particle Image Velocimetry (PIV).

4.1 Design of experiments

Experimentation is done at different tail beat frequencies and different Reynolds number. Single fish and side by side real life configurations are discussed in this research. Experimentation is carried out at three Reynolds number of 6200, 8700 & 11000 and on three tail beat frequencies 1Hz, 1.5Hz & 2Hz.

Table 4: Single Fish Cases

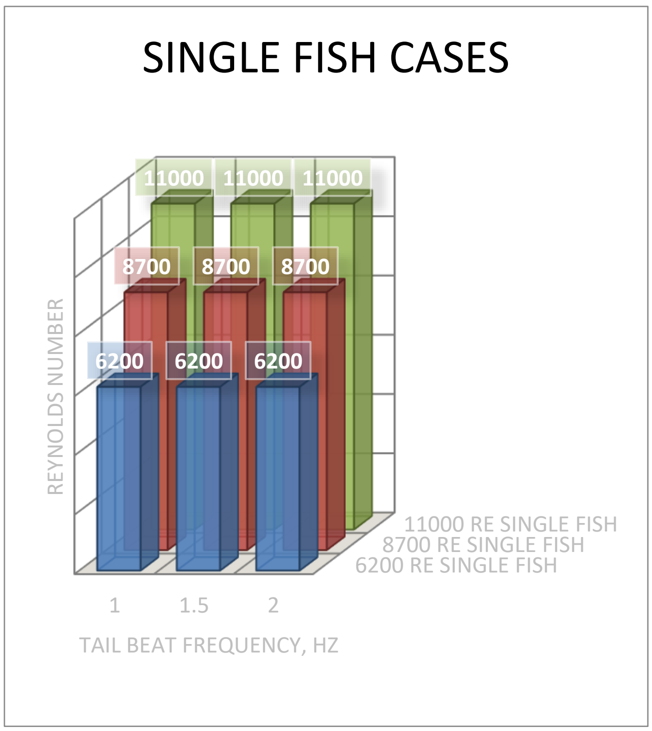
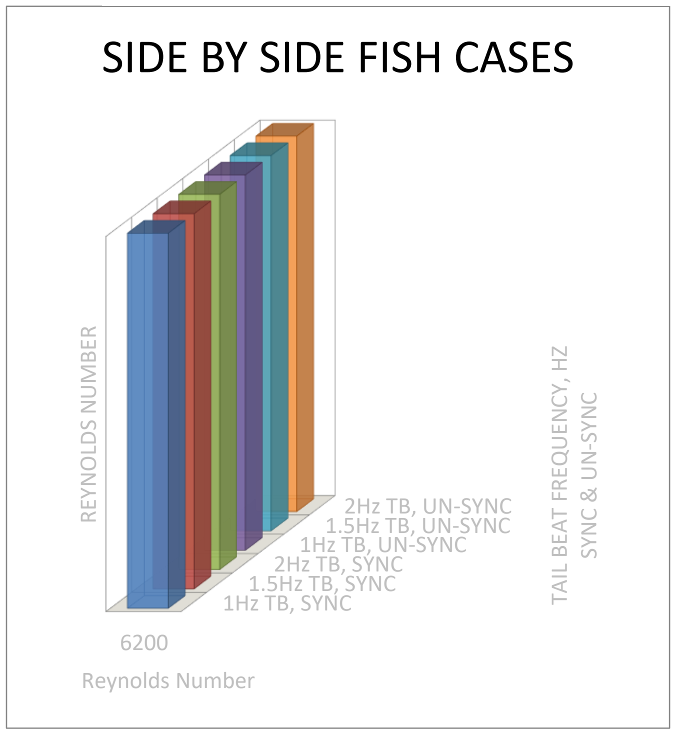
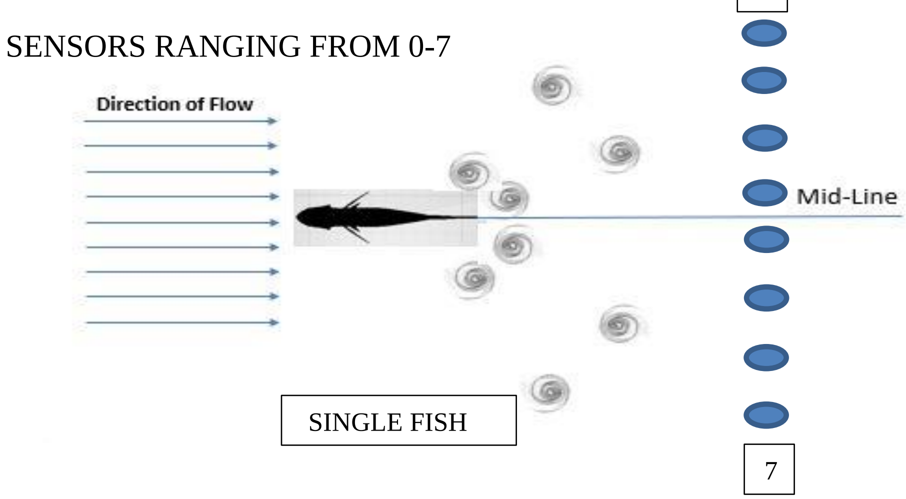


Table 2: Side-By-Side Fish Cases



9 single fish cases are performed and 6 side by side cases are performed on both synchronous and asynchronous mode of locomotion.

4.2 Pressure Measuring Setup:



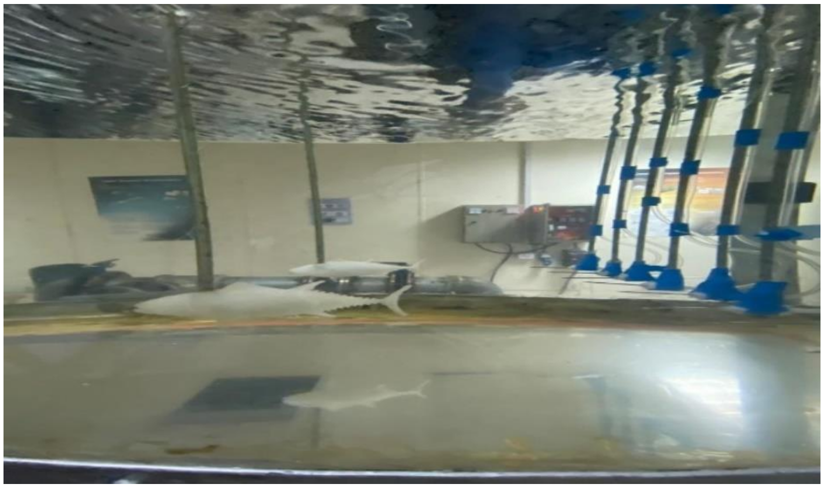


Figure 24: Pressure Measuring Grid

To study the hydrodynamics related to the flapping movement of fish at certain flapping frequency we use trainer 6001 pressure measuring bench which consists of 8 electric sensors to study the pressure difference created by the movement of fish, pressure difference created by the vortices induce by the fish at a certain Reynolds number is sensed by those sensors and thus DAQ convert those pressure changes into Voltage or Current. We placed 8 pressure measuring tubes on threaded steel rods around and back of the fish such that 4 tubes on each side of fish placed in various real-life conditions. Many cases like side-by-side arrangement, tandem & staggard cases are performed at three tail beat frequencies i.e., 1hz, 1.5hz & 2hz. The results obtain via DAQ are in form of voltages & current to change those readings to pressure we must interpolate sensors voltage/current vs pressure capacity to counter tally them to obtain generated pressure readings.

Current waveforms obtain via LabView of DAQ

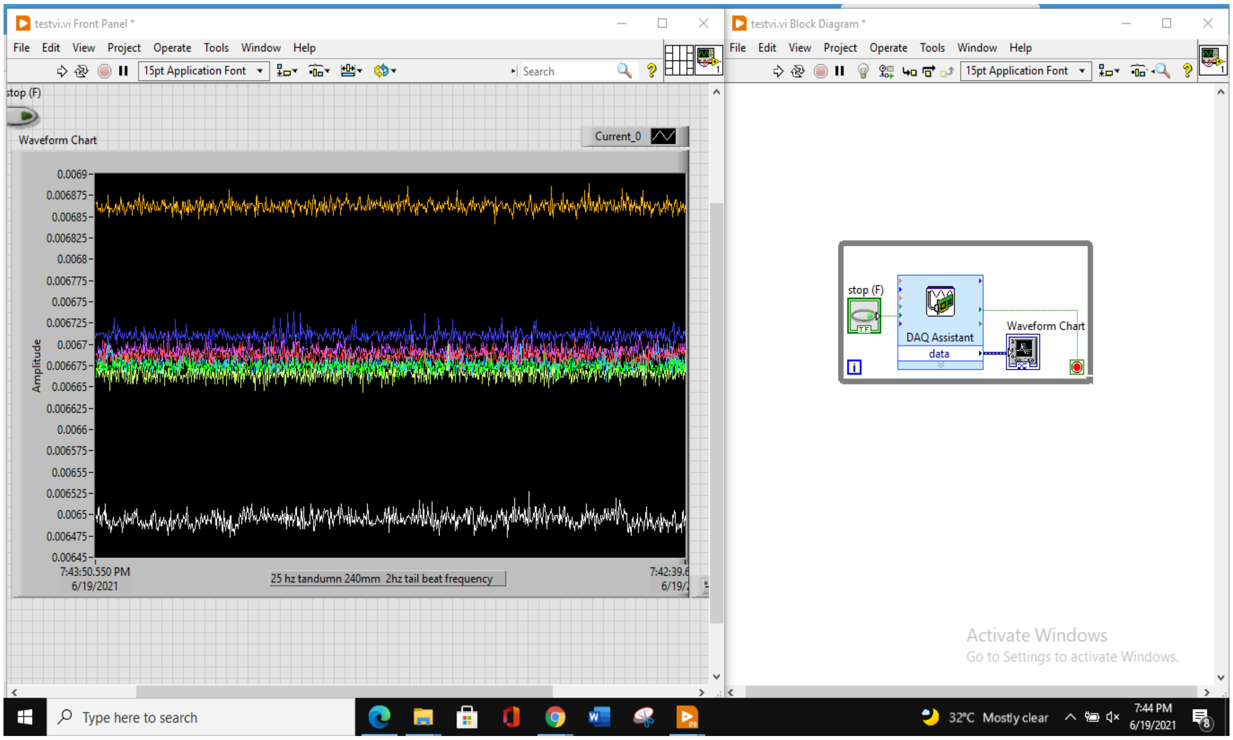


Figure 25: DAQ Output on Lab View Software

This setup isn't producing good results because the pressure sensors are not being able to measure the pressure change created by the vortices in the wake of flapping Tuna fish. Values change is seen at three decimal point, thus based on that we didn't use this method.

4.3 Method 1 (MATLAB Video Processing Via Image J)

- Record slow motion high frame rate video using Sony Rx-IV camera placed underneath water tunnel test section.
- Seeding particles made a certain swirling pattern called as vortices under the DPSS 2D Laser Bed.
- Process that slow-motion HFR video in MATLAB and produce monochromatic frames.
- Open Image J & define scale in pixel/mm ratio.
- Mark the scale on picture and save it for future reference.
- Open image series of frames generated by MATLAB in Image J.
- Mark circles around vortices and measure them in the form of area.

• From software you can also calculate x and y axis propagation and time.

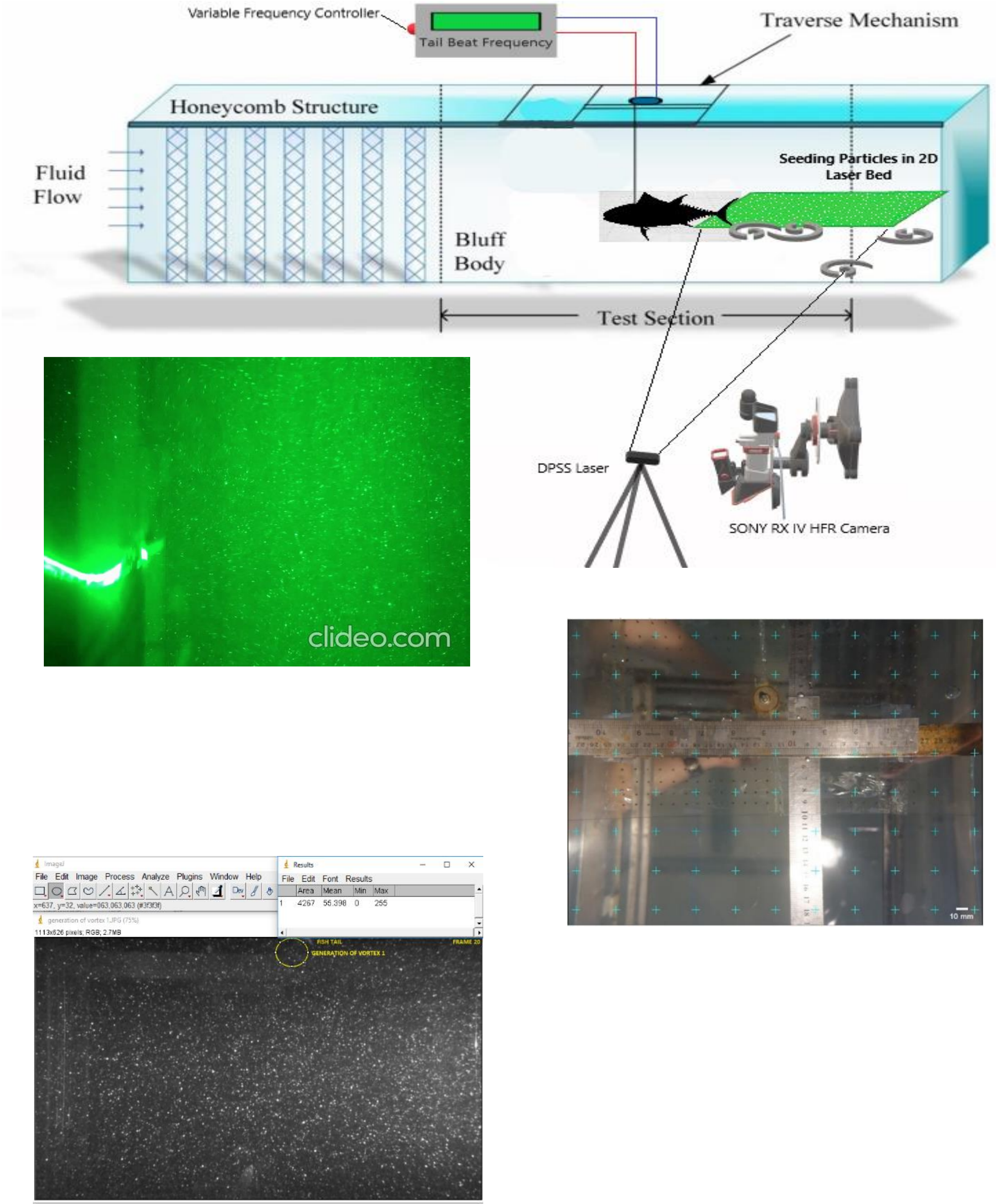


Figure 26: Single Fish Schematics & Image J Software

4.4 Method 2 (Particle Image Velocimetry)

2nd experimentation is based on validation of numerical approach used by Feng et. al. Experimental technique of flow visualization is carried out to study wake generated by caudal fin. For PIV laser is set at mid of caudal fin. Pulse delay is set at 3000 microseconds. Pulse width is set at 2000 microsecond. Camera is set beneath Water Tunnel to study wake generated by caudal fin on 2D laser sheet. 1000 images were taken and processed in Micro-Vec's PIV Software, which generates DAT file. Then DAT file is open in TecPlot 360 Software to find Vorticity.

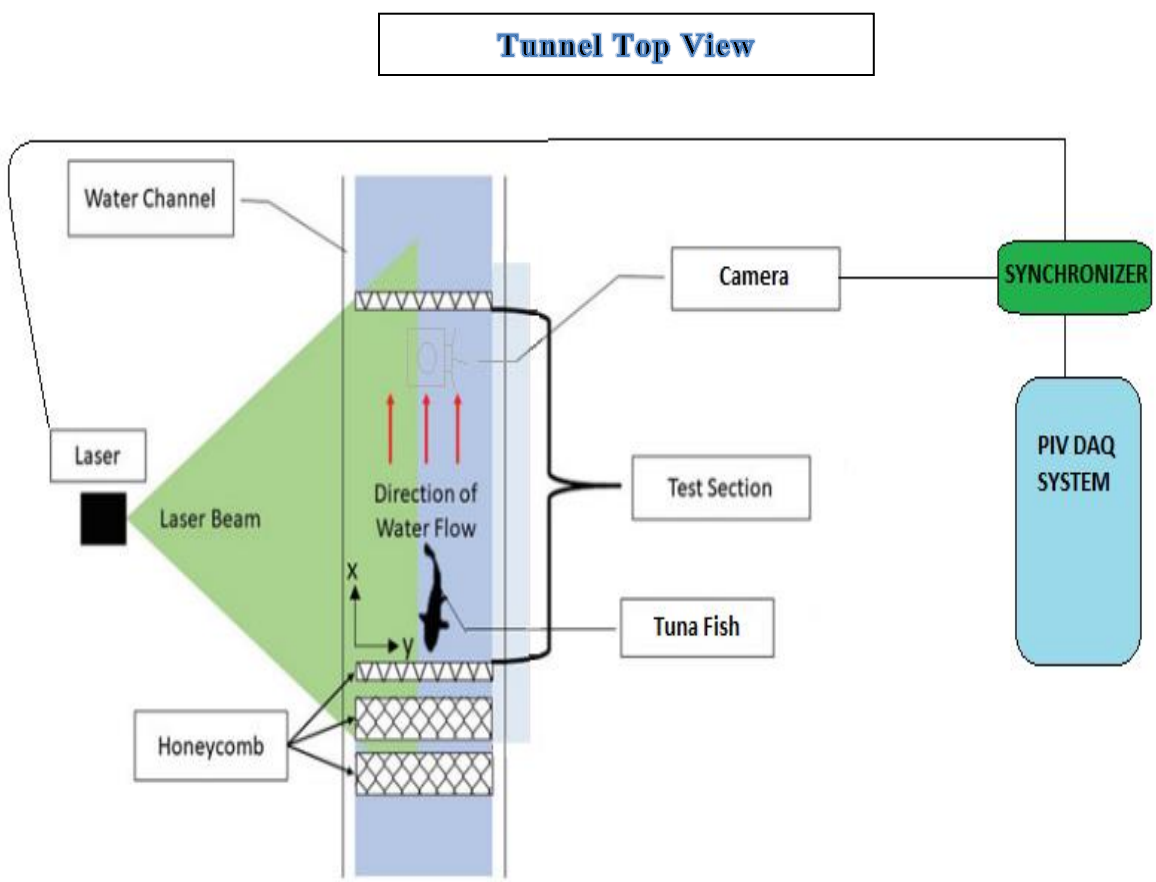


Figure 27: PIV Setup for Single Fish Case

Figure 28: Water Tunnel Pump & PIV Equipment

Converging-Diverging water channel 2.0m*0.4m*0.4m is used with test section's all sides are transparent of cross-sectional area of 80mm*150mm is employed for PIV experiment. All experimental PIV setup is labeled, and everything is placed carefully in its place to perform flow visualization of Tuna fish to study its wake characteristics. 5Watt Diode Pumped Solid State Laser with 532nm wavelength is employed on the left-hand side of tunnel which illuminates the streamline moving particles on 2D bed, placed perpendicularly to the Tuna fish Tail, for camera to trace seed particles to translate their motion into vortex generation and shedding. CCD Camera (Imperex CLB-B1320M) having a spatial resolution of 1280pixel*720pixel with a maximum sampling frequency of the system is 30fps with a Nikon AF Micro 60f/2.8D lens, setup is placed beneath the test section to not interfere with any other apparatus as well as with the hindrance of laser bed, in order to get images at certain interval to send it to computer for further analysis.

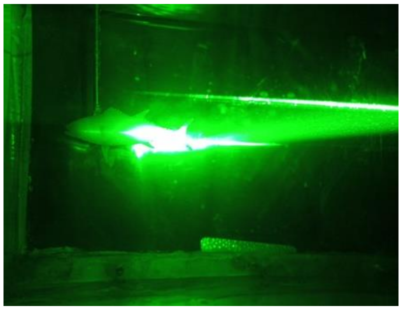
In order to read the flow particles must be used in flow, for camera to trace their path. For that we have used MicroVec's seed particles (Hollow Glass Spheres) of density (1.05 g/cc) equal to water and of the Material Mean Composition size (15μm) used in tunnel so that particles should remain suspended/buoyant in water, we have use hollow glass sphere' to have better light scatter properties with refractive index of 1.5.

Data received from camera in the form of images is compatible with PIV system which is placed in order to obtain images at single frame of camera & double pulse mode of laser. The interval is set to be at 3000μs, with the interval set between images is 2000μs. Required data is extracted from images via MicroVec's software and then stream traces are plotted in plot 360 software is used.

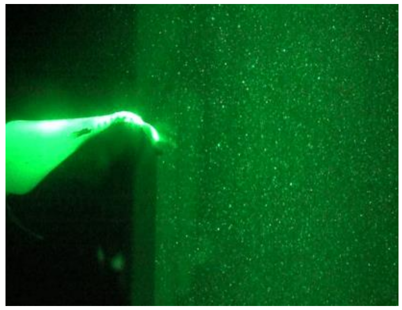
2nd experiment includes the use of PIV particle image velocimetry, to observe the vortices generated by the Tuna fish under specific tail beat frequency. Firstly with designed flapping mechanism set the tail beat frequency to 1Hz, the counter check it with video capturing and processing via MATLAB to determine the correct flapping frequency, once checked start the tunnel pump at 0.055m/s speed and perform PIV setup, It includes the use of camera to trace particles moving around bluff body (fish) making certain pattern of vortices, the camera then captures those vortices and then process thousands of images taken over the course of time to draw a vector & vorticity contour in Tec-Plot 360 Software, to understand how fluid interact with fish at different tail beat frequencies & Reynold numbers.

In general, there are three assumptions for PIV technology:

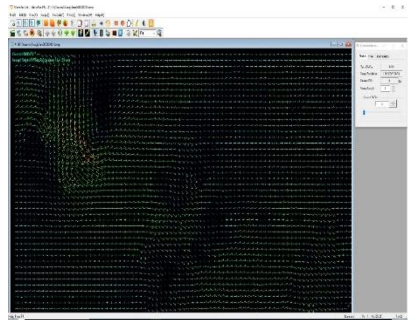
1. Tracer particles follow the fluid motion.
2. Tracer particles are uniformly distributed in the flow field.
3. Interrogation window having a unique speed ($U = \frac{\Delta x}{\Delta t}$).



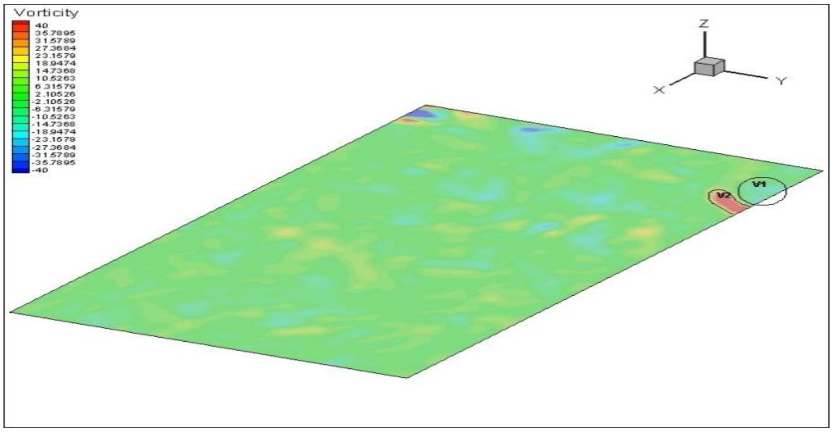
Laser bed at mid of Caudal Fin



Live Camera Feed



Computed Instantaneous Flow Field



Final Image/view after post-processing

Figure 29: Step By Step Post Processing of PIV

CHAPTER 5: RESULTS AND DISCUSSION

Results and comparison are drawn on the basis of vortex size in the form of area, vortex velocities and its propagation in x and y axis. All the graphical data is obtained via MATLAB video processing via using Image J to find these parameters.

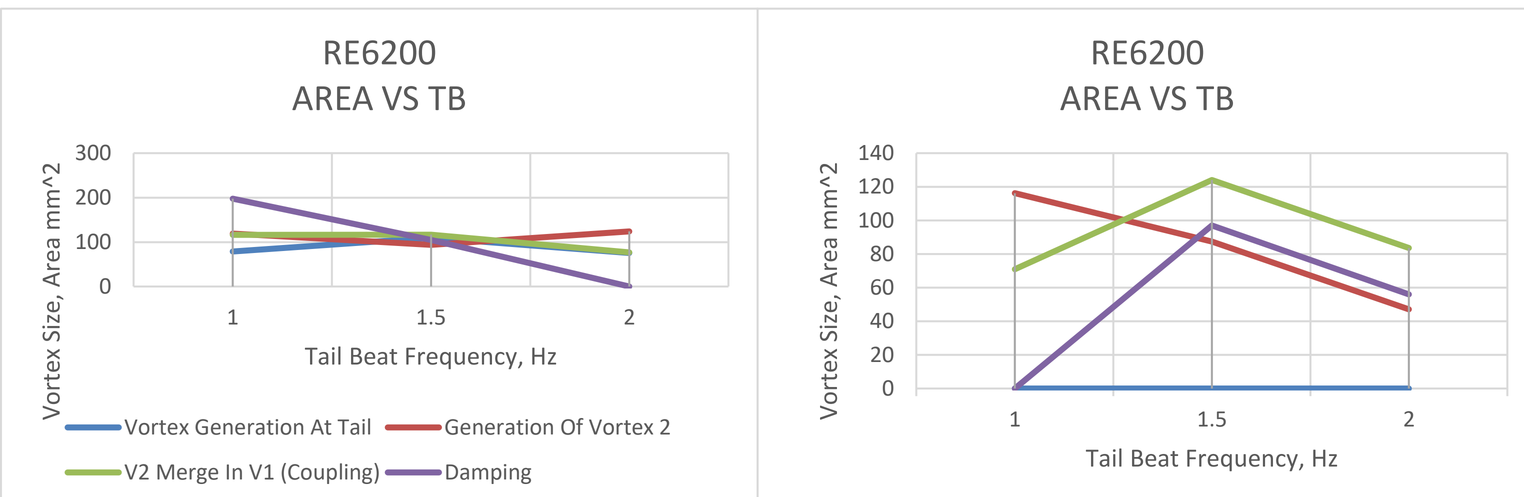
5.1 MATLAB Video Processing Via Image J Results

5.1.1 Single fish cases

5.1.1.1 Vortex Size (Area) vs Tail beat frequency

1. Results at Reynold number 6200 and 3 Tail beat frequencies of 1Hz, 1.5Hz & 2 Hz.

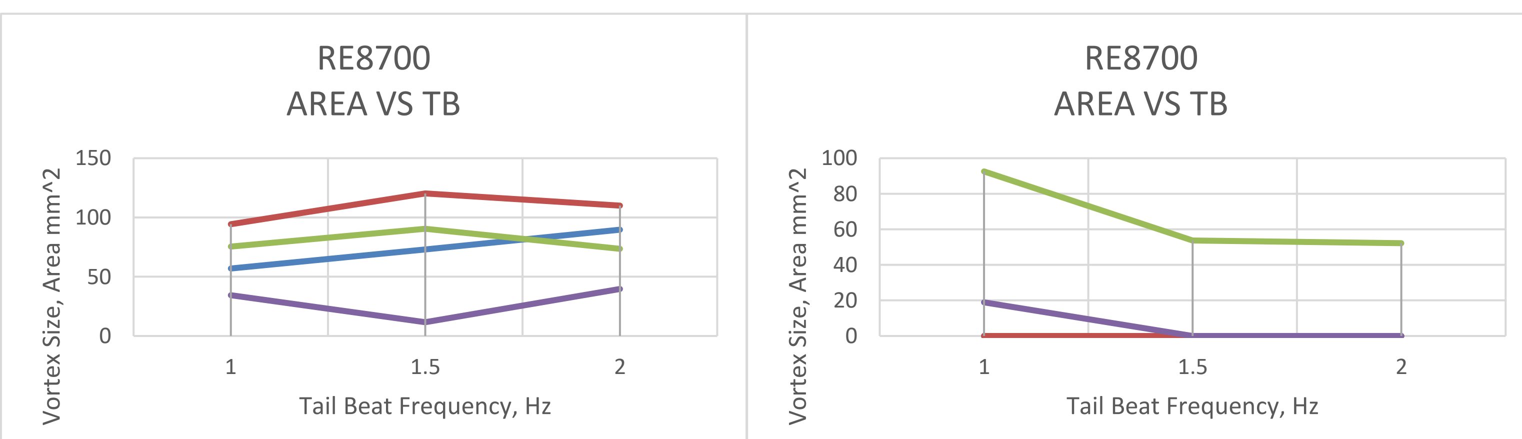
Vortex 1 **Vortex 2**



Graph 1: Reynolds Number 6200 vs 3 Tail Beat Frequency

2. Results at Reynold number 8700 and 3 Tail beat frequencies of 1Hz, 1.5Hz & 2 Hz.

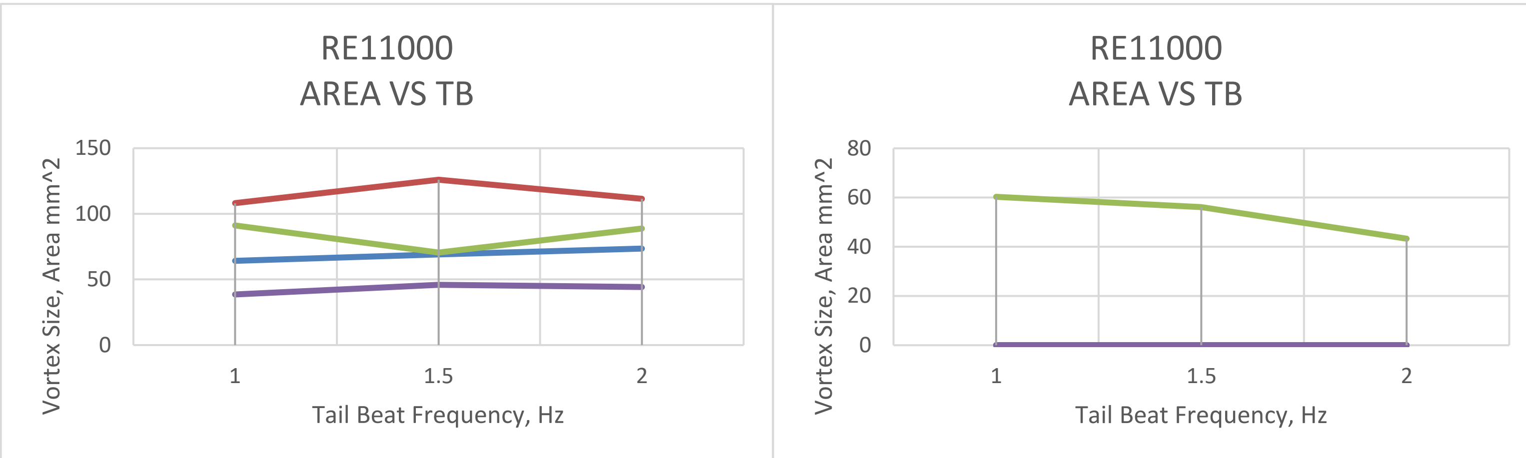
Vortex 1 **Vortex 2**



Graph 2: Reynolds Number 8700 vs 3 Tail Beat Frequency

3. Results at Reynold number 11000 and 3 Tail beat frequencies of 1Hz, 1.5Hz & 2 Hz.

Vortex 1 **Vortex 2**

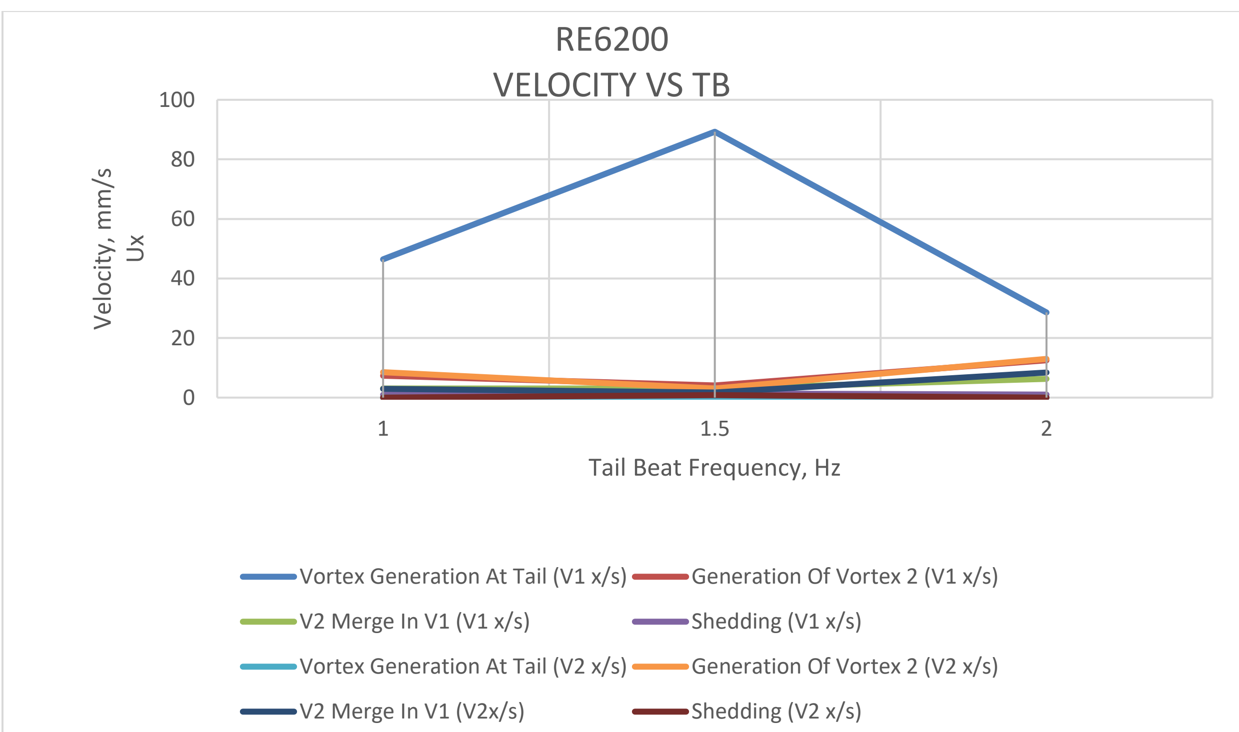


Graph 3: Reynolds Number 11000 vs 3 Tail Beat Frequency

5.1.1.2 Vortex Velocity vs Tail beat frequency

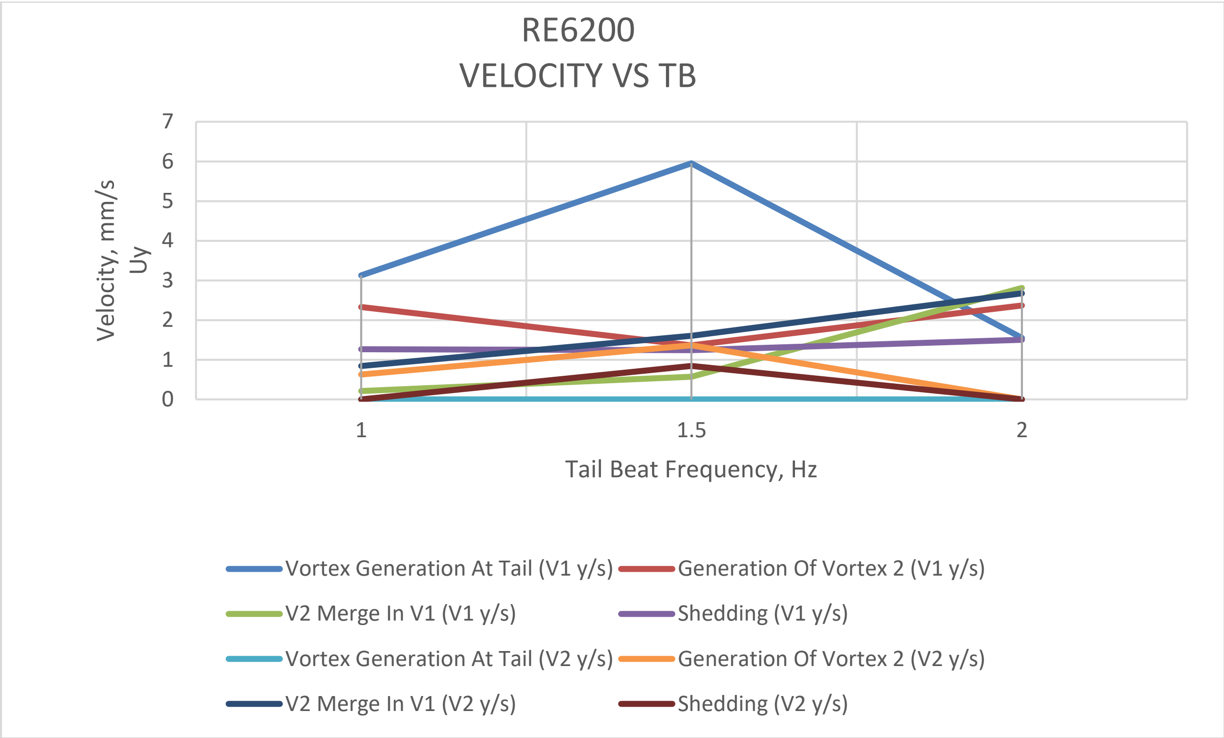
1. Results at Reynold number 6200 and 3 Tail beat frequencies of 1Hz, 1.5Hz & 2 Hz

V1 & V2 X Axis



Graph 4: Velocity (X) vs TB-Reynolds Number 6200 vs 3 Tail Beat Frequency

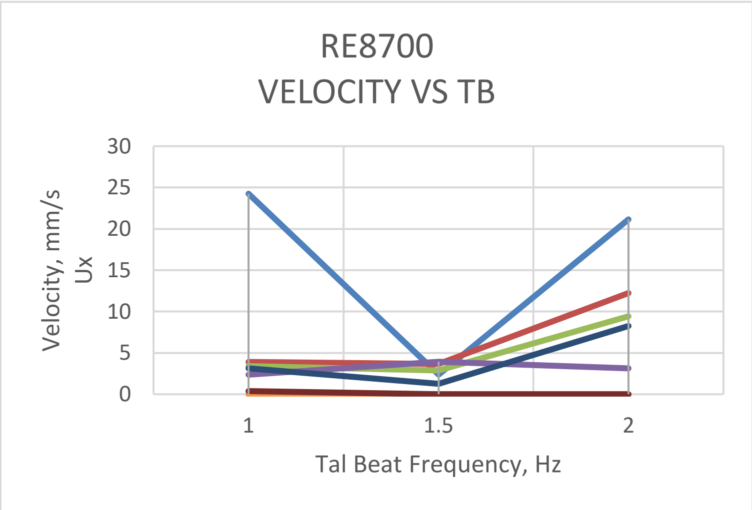
V1 & V2 Y Axis



Graph 5: Velocity (Y) vs TB-Reynolds Number 6200 vs 3 Tail Beat Frequency

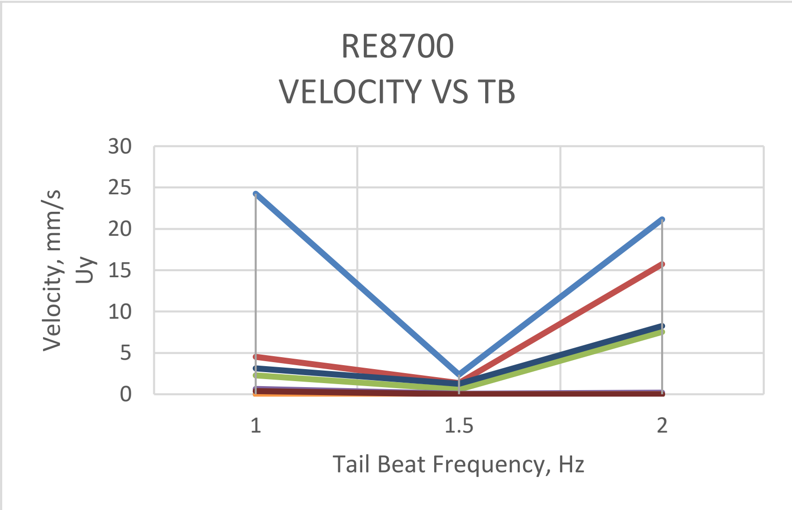
2. Results at Reynold number 8700 and 3 Tail beat frequencies of 1Hz, 1.5Hz & 2 Hz

V1 & V2 X Axis



Graph 6: Velocity (X) vs TB-Reynolds Number 8700 vs 3 Tail Beat Frequency

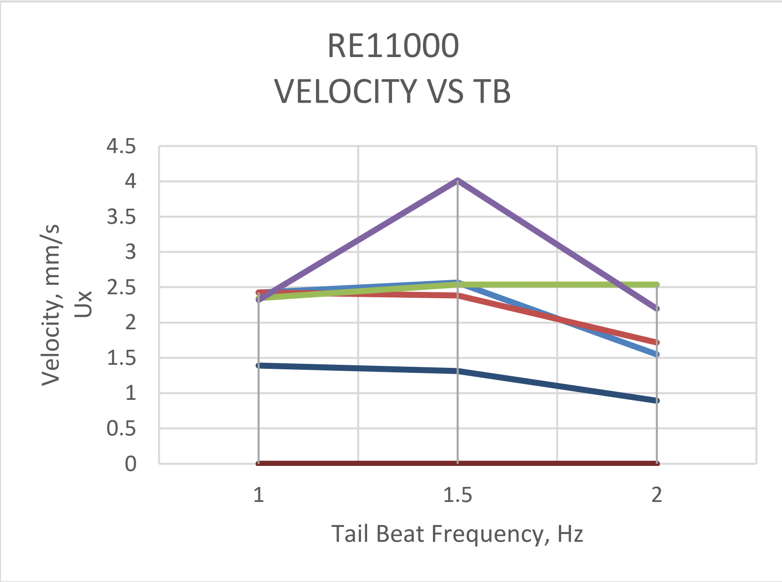
V1 & V2 Y Axis



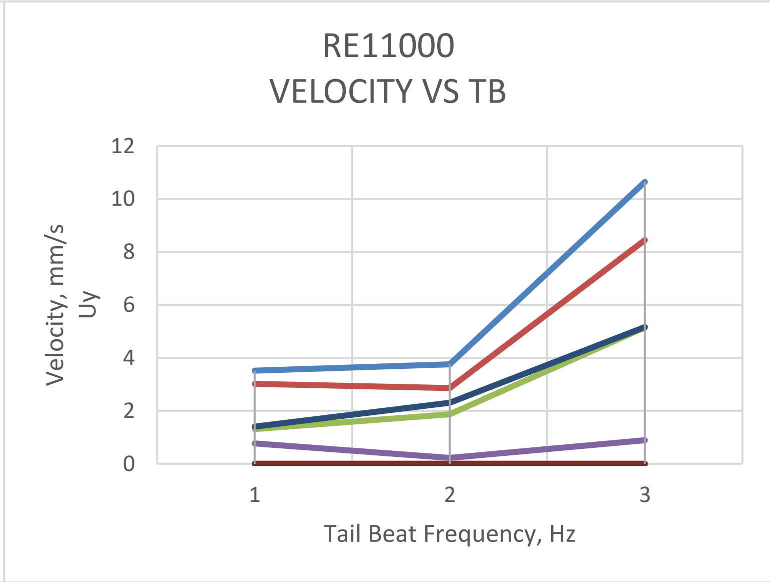
Graph 7: Velocity (Y) vs TB-Reynolds Number 8700 vs 3 Tail Beat Frequency

3. Results at Reynold number 11000 and 3 Tail beat frequencies of 1Hz, 1.5Hz & 2 Hz

V1 & V2 X Axis **V1 & V2 Y Axis**



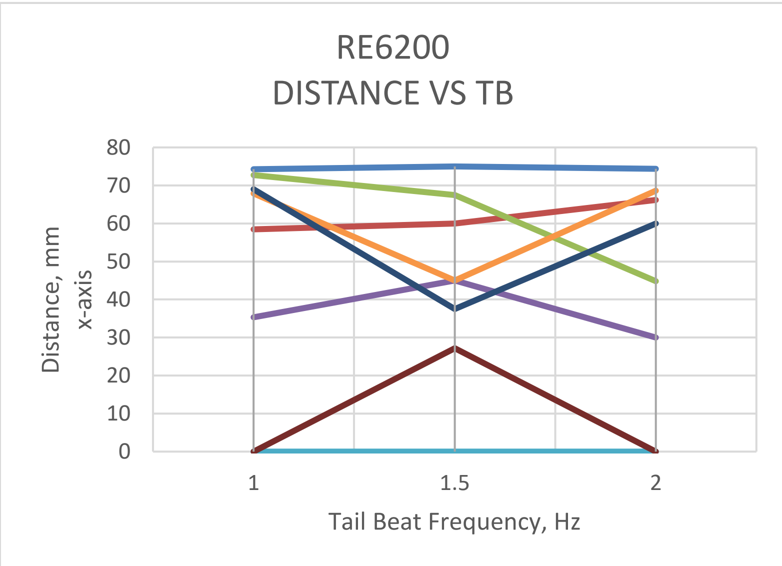
Graph 8: Velocity (X) vs TB-Reynolds Number 11000 vs 3 Tail Beat Frequency



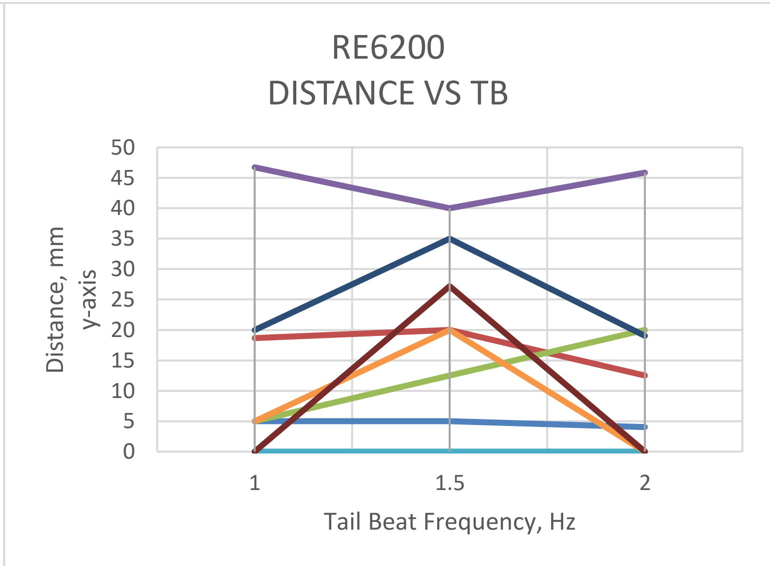
Graph 9: Velocity (Y) vs TB-Reynolds Number 11000 vs 3 Tail Beat Frequency

1. Results at Reynold number 6200 and 3 Tail beat frequencies of 1Hz, 1.5Hz & 2 Hz

X Axis **Y A**



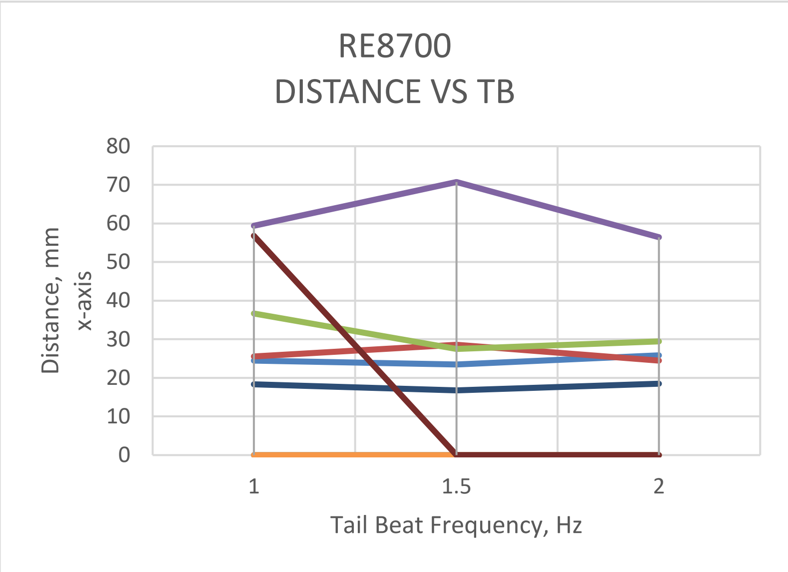
Graph 10: Distance (X) vs TB-Reynolds Number 6200 vs 3 Tail Beat Frequency



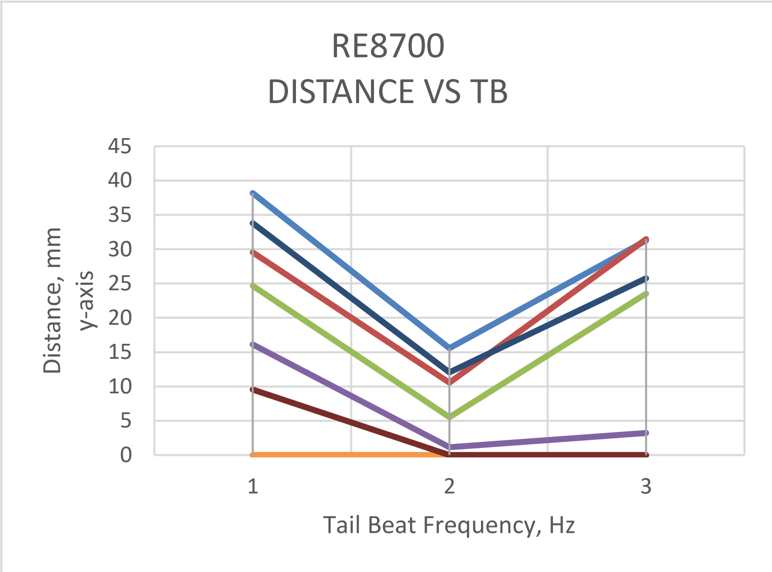
Graph 11: Distance (Y) vs TB-Reynolds Number 6200 vs 3 Tail Beat Frequency

2. Results at Reynold number 8700 and 3 Tail beat frequencies of 1Hz, 1.5Hz & 2 Hz

X Axis **Y Axis**



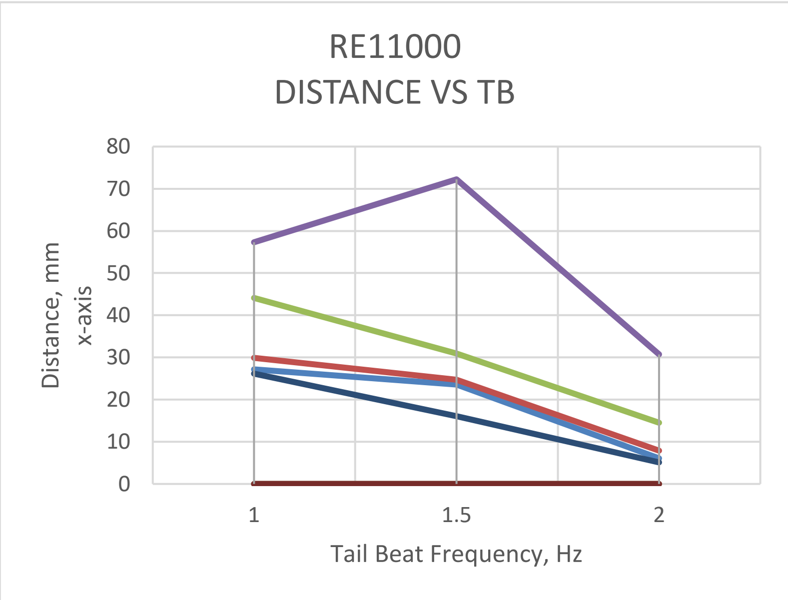
Graph 12: Distance (X) vs TB-Reynolds Number 8700 vs 3 Tail Beat Frequency



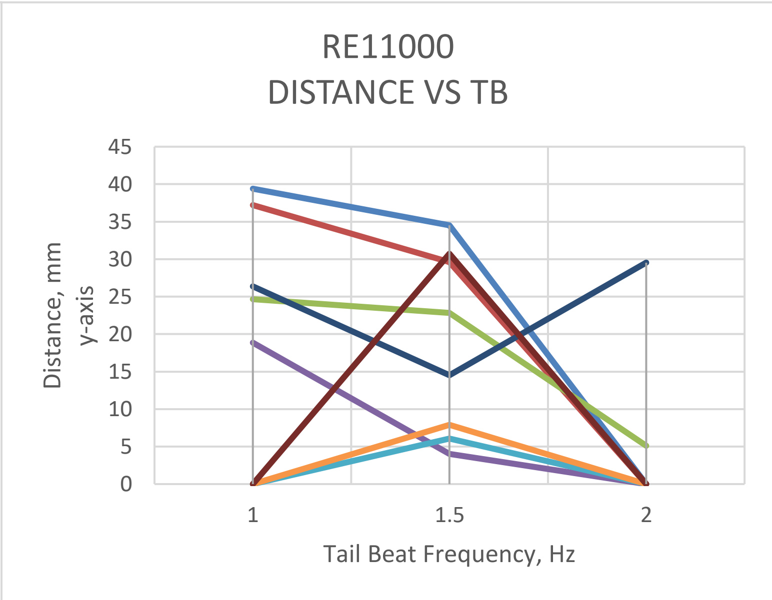
Graph 13: Distance (Y) vs TB-Reynolds Number 8700 vs 3 Tail Beat Frequency

3. Results at Reynold number 11000 and 3 Tail beat frequencies of 1Hz, 1.5Hz & 2 Hz

X Axis **Y Axis**



Graph 14: Distance (X) vs TB-Reynolds Number 11000 vs 3 Tail Beat Frequency



Graph 15: Distance (Y) vs TB-Reynolds Number 11000 vs 3 Tail Beat Frequency

Findings:

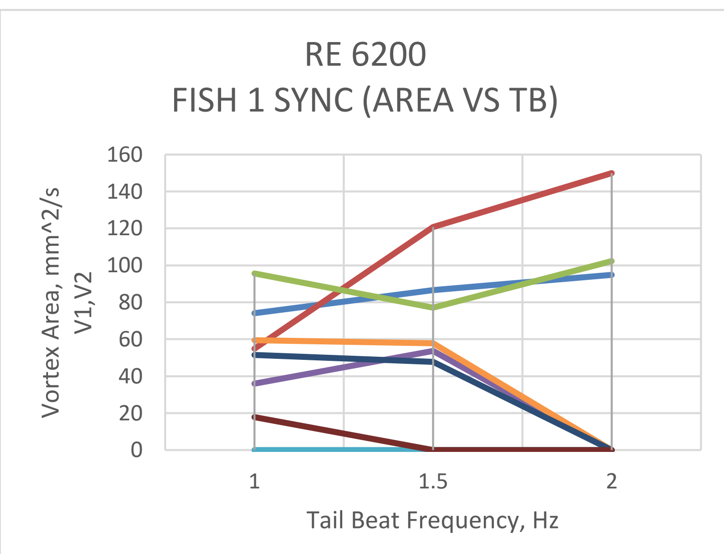
1. Higher the tail beat frequency & Reynolds number would result in lower hydrodynamic efficiency.
2. Better hydrodynamic efficiency of 58% is seen for 1hz tail beat frequency & 6200 Reynolds number.
3. Vortex 2 damped fast on higher Reynolds numbers, while Vortex 1 tends to have better size at 1.5hz tail beat frequency and higher Reynolds number.
4. Low hydrodynamic advantages of (26%) are seen for both vortex size and vortex velocity at 2Hz tail beat frequency & Reynolds number 11000, for single fish case.
5. Larger velocities are seen at 2hz tail beat frequency and 11000 Reynolds number.
6. Larger distances travel by V1 & V2 at lower Reynolds number and vice versa.
7. For Reynolds number greater than 6200 better hydrodynamic advantages (54.818%) are seen at 1.5hz tail beat frequency for single fish case.

5.1.2 Side by side fish cases

5.1.2.1 Vortex Size (Area) vs Tail beat frequency

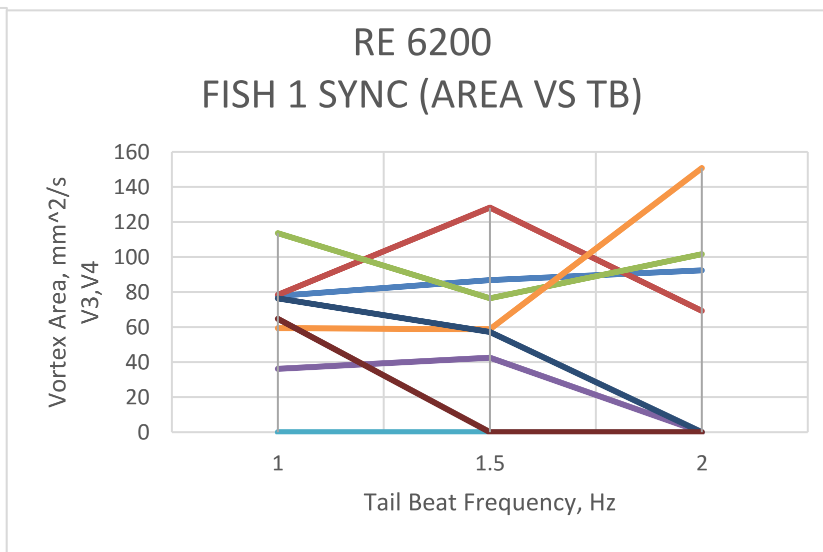
Sync & Un-Sync

1. Results at Reynold number 6200 and 3 Tail beat frequencies of 1Hz, 1.5Hz & 2 Hz



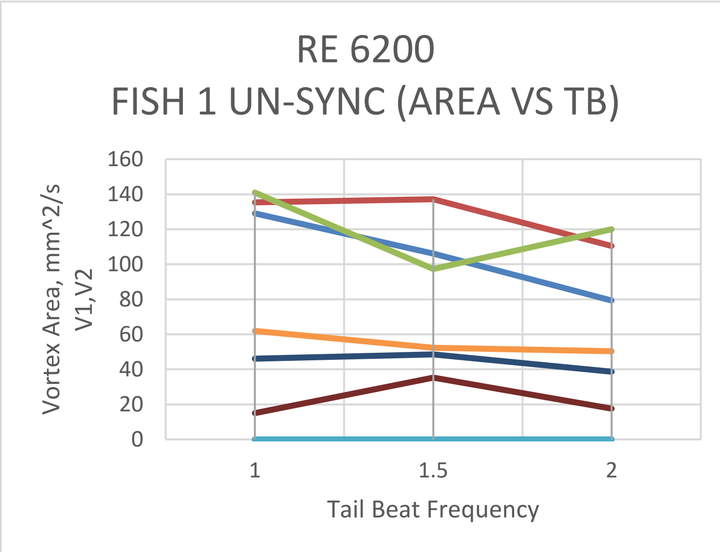
Graph 16: Area (Fish 1 Sync) vs TB-Reynolds Number 6200 vs 3 Tail Beat Frequency

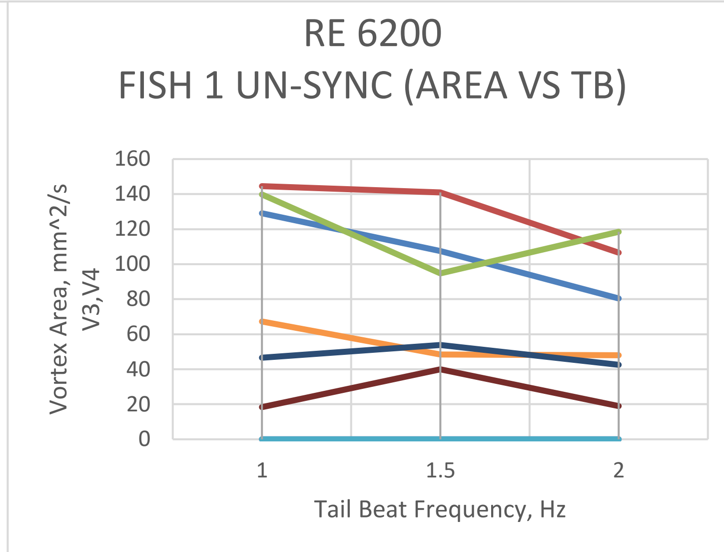
Fish 1 Sync



Graph 17: Area (Fish 2 Sync) vs TB-Reynolds Number 6200 vs 3 Tail Beat Frequency

Fish 2 Sync





Graph 18: Area (Fish 1 Un-Sync) vs TB-Reynolds Number 6200 vs 3 Tail Beat Frequency

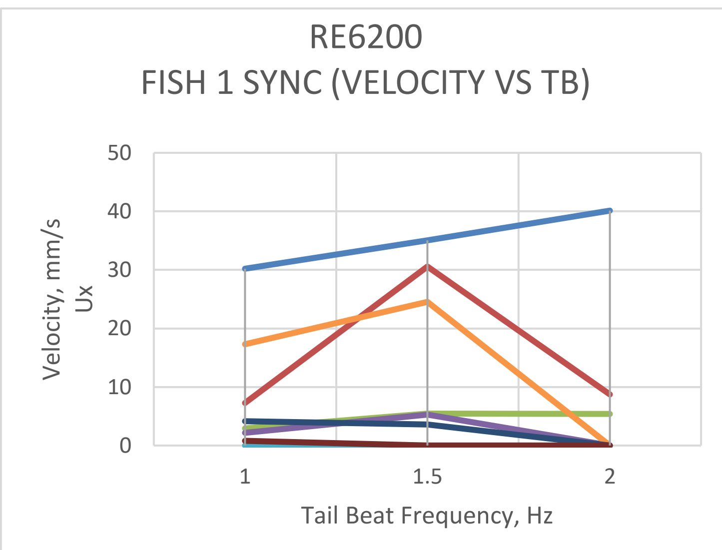
Graph 19: Area (Fish 2 Un-Sync) vs TB-Reynolds Number 6200 vs 3 Tail Beat Frequency

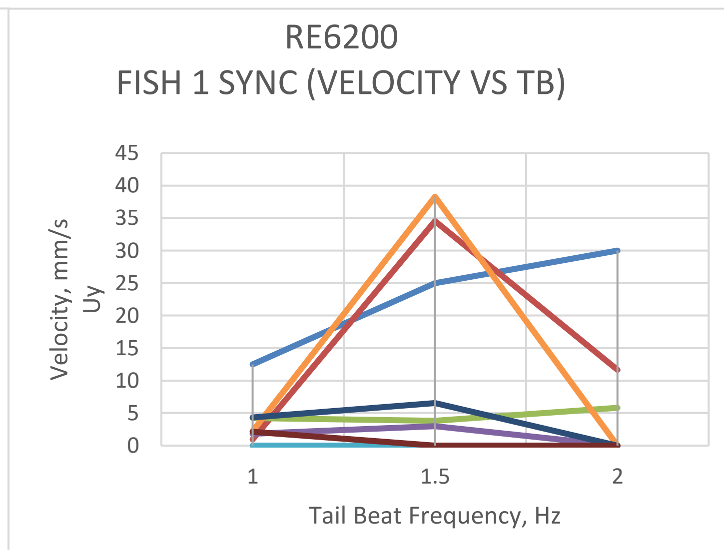
Fish 1 Un-Sync

Fish 2 Un-Sync

5.1.2.2 Vortex Velocity vs Tail beat frequency

1. Results at Reynold number 6200 and 3 Tail beat frequencies of 1Hz, 1.5Hz & 2 Hz



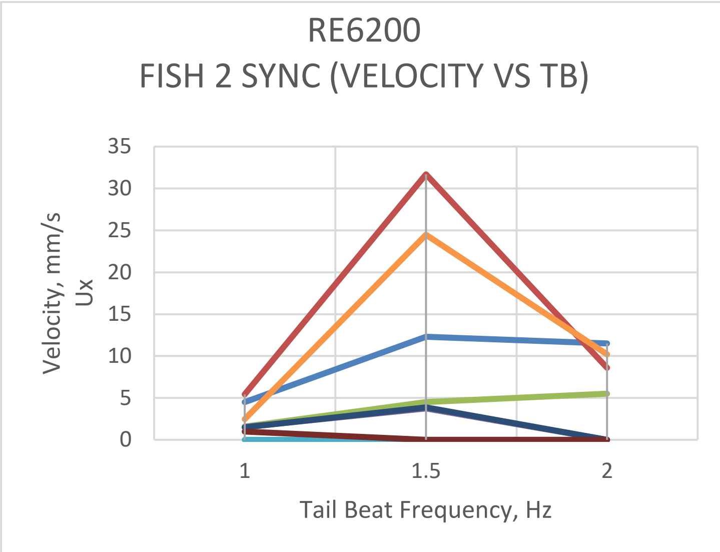


Fish 1 Sync

Fish 1 Sync

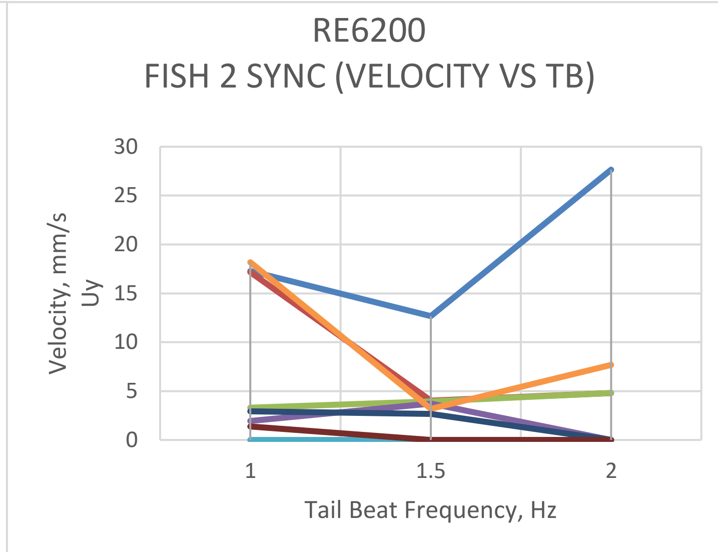
Graph 20: Velocity (X) (Fish 1 Sync) vs TB-Reynolds Number 6200 vs 3 Tail Beat Frequency

Graph 21: Velocity (Y) (Fish 1 Sync) vs TB-Reynolds Number 6200 vs 3 Tail Beat Frequency



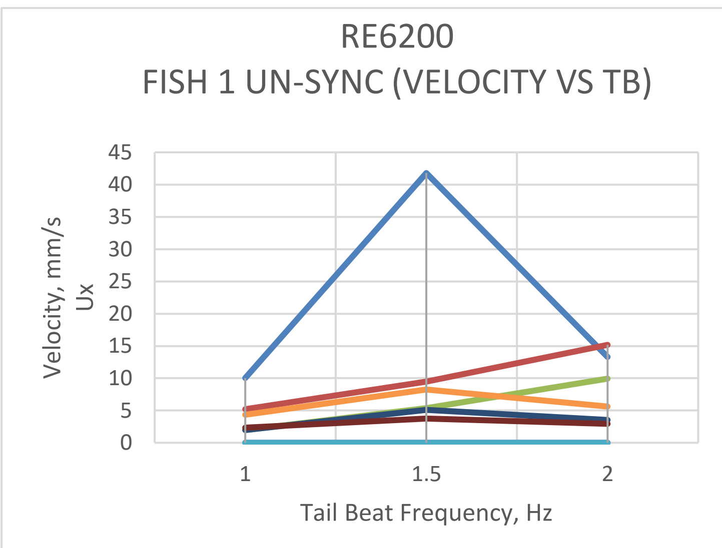
Graph 22: Velocity (X) (Fish 2 Sync) vs TB- Reynolds Number 6200 vs 3 Tail Beat Frequency

Fish 2 Sync



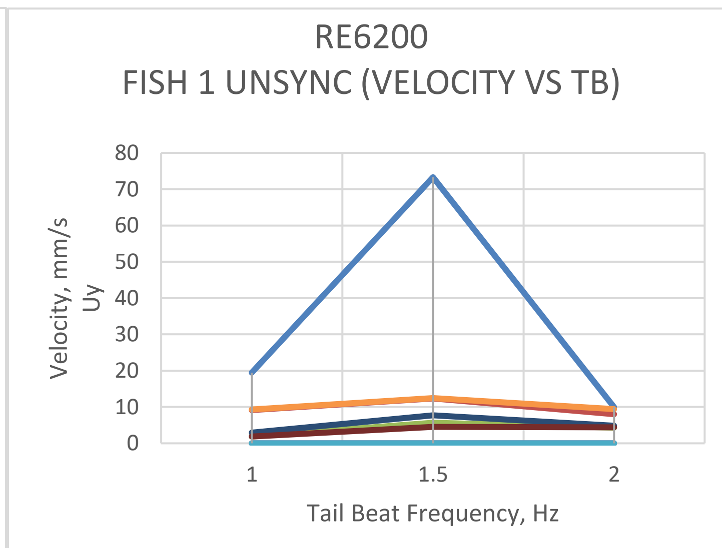
Graph 23: Velocity (Y) (Fish 2 Sync) vs TB- Reynolds Number 6200 vs 3 Tail Beat Frequency

Fish 2 Sync



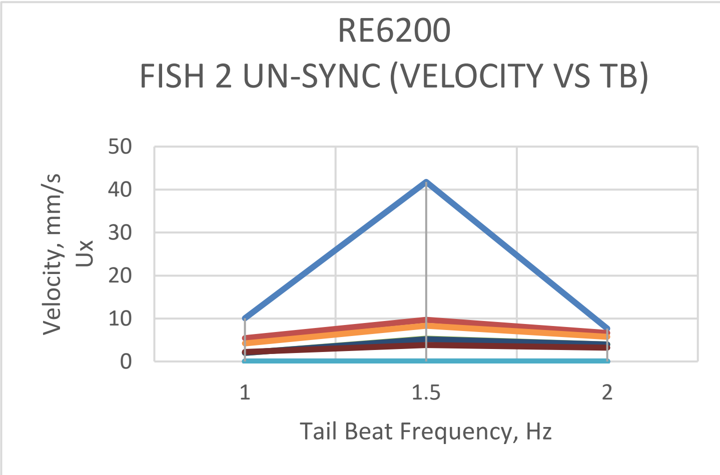
Graph 24: Velocity (X) (Fish 1 Un-Sync) vs TB- Reynolds Number 6200 vs 3 Tail Beat Frequency

Fish 1 Un-Sync



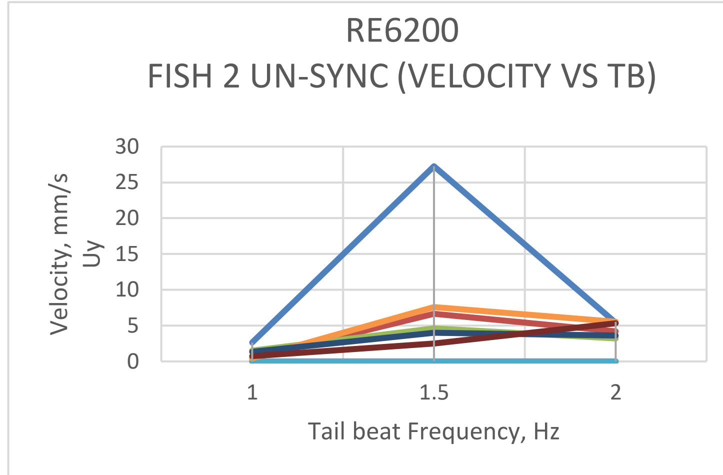
Graph 25: Velocity (X) (Fish 1 Un-Sync) vs TB- Reynolds Number 6200 vs 3 Tail Beat Frequency

Fish 1 Un-Sync



Graph 26: Velocity (X) (Fish 2 Un-Sync) vs TB-Reynolds Number 6200 vs 3 Tail Beat Frequency

Fish 2 Un-Sync

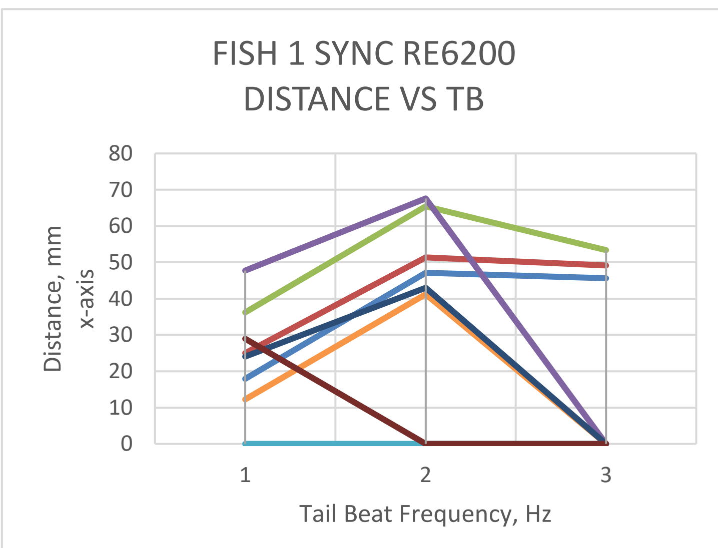


Graph 27: Velocity (Y) (Fish 2 Un-Sync) vs TB-Reynolds Number 6200 vs 3 Tail Beat Frequency

Fish 2 Un-Sync

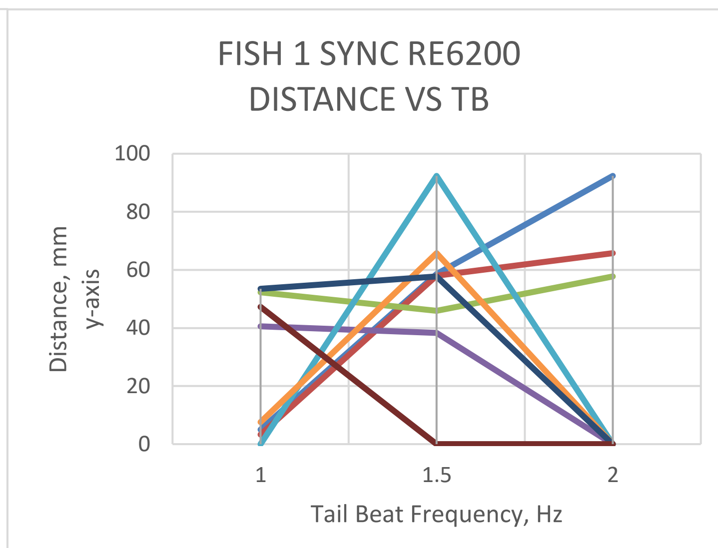
5.1.2.3 Vortex Distance vs Tail beat frequency

1. Results at Reynold number 6200 and 3 Tail beat frequencies of 1Hz, 1.5Hz & 2 Hz.



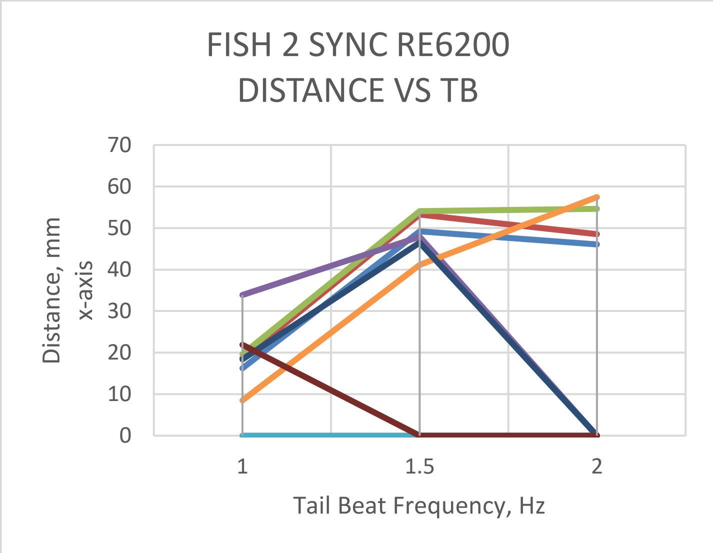
Graph 28: Distance (X) (Fish 1 Sync) vs TB-Reynolds Number 6200 vs 3 Tail Beat Frequency

Fish 1 Sync

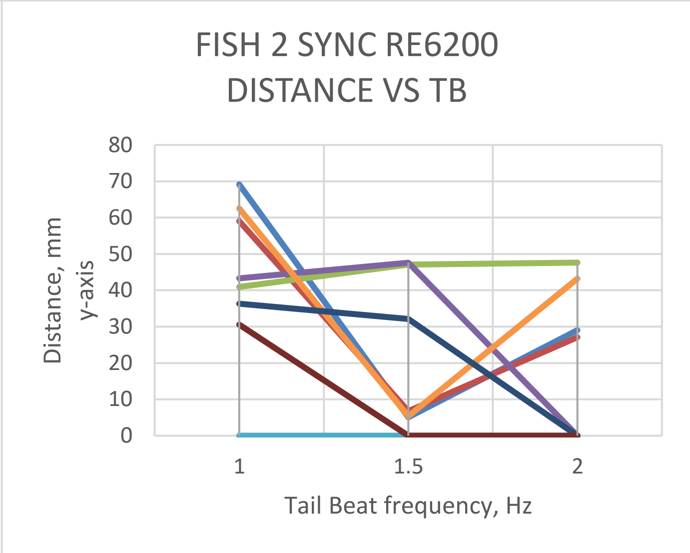


Graph 29: Distance (Y) (Fish 1 Sync) vs TB-Reynolds Number 6200 vs 3 Tail Beat Frequency

Fish 1 Sync



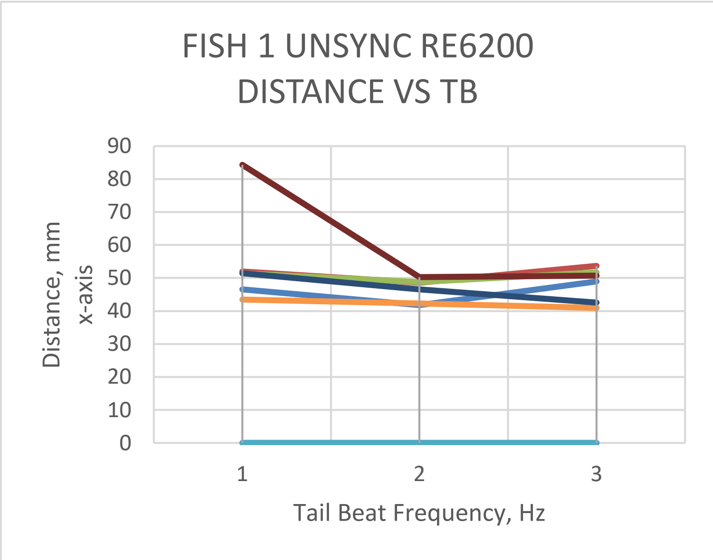
Graph 30: Distance (X) (Fish 2 Sync) vs TB- Reynolds Number 6200 vs 3 Tail Beat Frequency



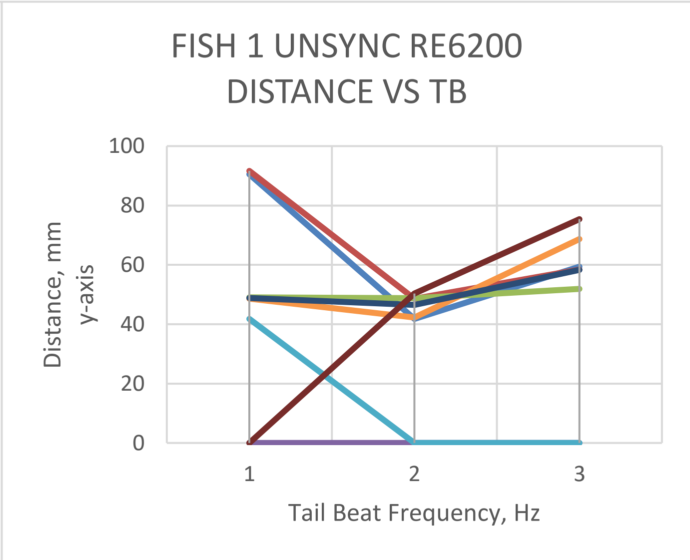
Graph 31: Distance (Y) (Fish 2 Sync) vs TB- Reynolds Number 6200 vs 3 Tail Beat Frequency

Fish 2 Sync

Fish 2 Sync



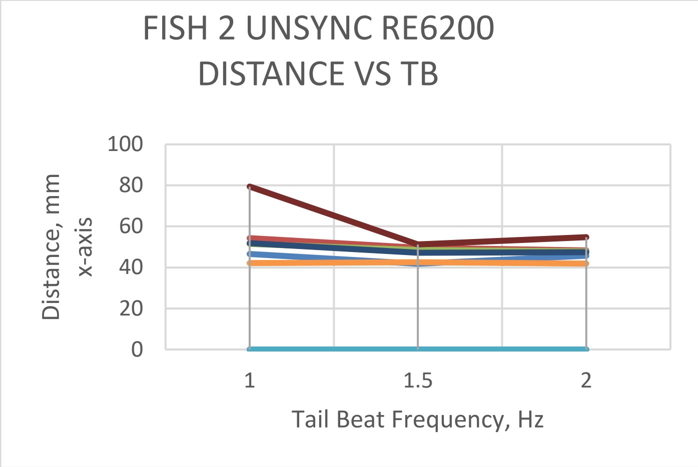
Graph 32: Distance (X) (Fish 1 Un- Sync) vs TB- Reynolds Number 6200 vs 3 Tail Beat Frequency



Graph 33: Distance (Y) (Fish 1 Un-Sync) vs TB- Reynolds Number 6200 vs 3 Tail Beat Frequency

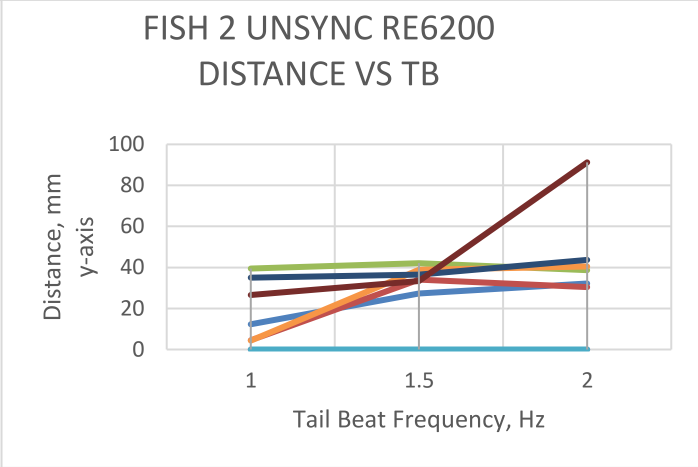
Fish 1 Un-Sync

Fish 1 Un-Sync



Graph 34: Distance (X) (Fish 2 Un-Sync) vs TB-Reynolds Number 6200 vs 3 Tail Beat Frequency

Fish 2 Un-Sync



Graph 35: Distance (Y) (Fish 2 Un-Sync) vs TB-Reynolds Number 6200 vs 3 Tail Beat Frequency

Fish 2 Un-Sync

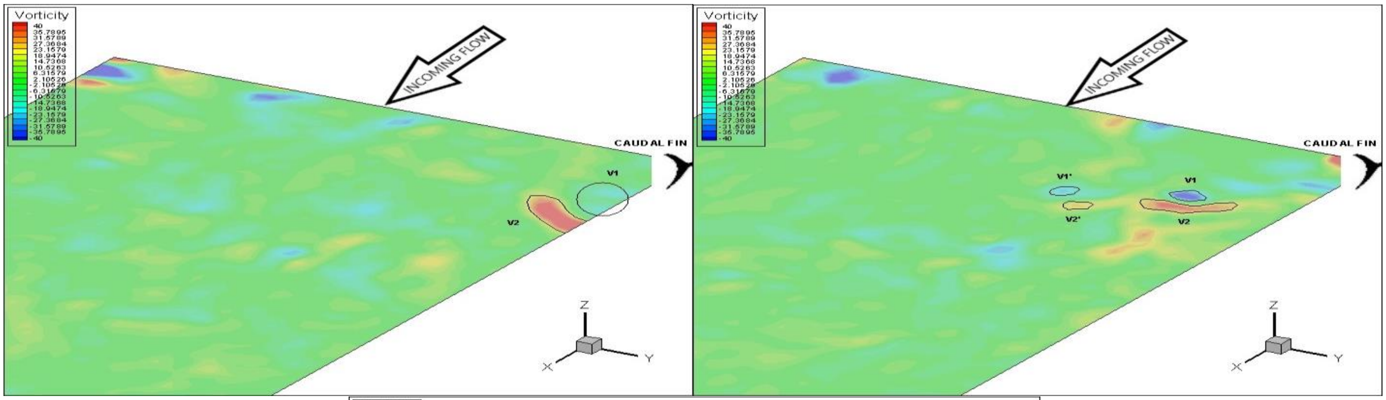
Findings:

1. Distance larger than 120mm (1fish-length) in side-by-side case would results in lower hydrodynamic efficiency (10%).
2. Better hydrodynamics (54%) are seen at 2Hz tail beat frequency and Reynolds number of 6200 for side-by-side case in synchronous mode of locomotion.
3. Whereas in asynchronous mode of locomotion better efficiency (30.97%) is achieved at 1Hz tail beat frequency and Reynold number of 6200.
4. In synchronous mode of locomotion, vortex propagation is better than in asynchronous because of constructive coupling of vortex V1 & V3.
5. Where as in asynchronous mode of locomotion, vortex propagation is not good because of destructive coupling of V1 and V3, results in lower efficiency.
6. Higher velocities and higher distances travel by vortices are seen at 2hz tail beat frequency for all Reynolds number.

5.2 Results of Particle Image Velocimetry

Results in the form of vorticity are Plotted on Tec Plot 360 Software**.**

5.2.1 Results AT RE6200 & 1HZ TBF



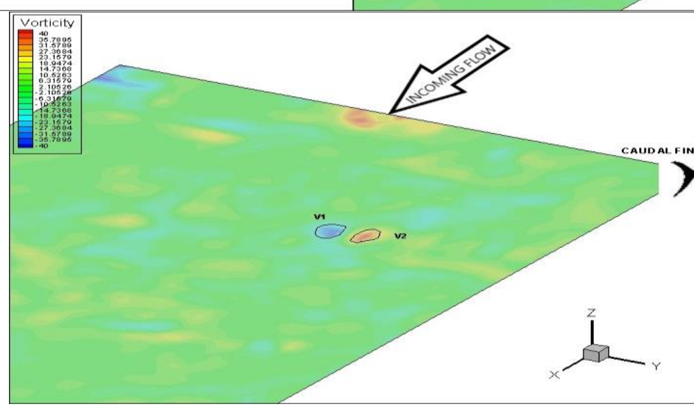
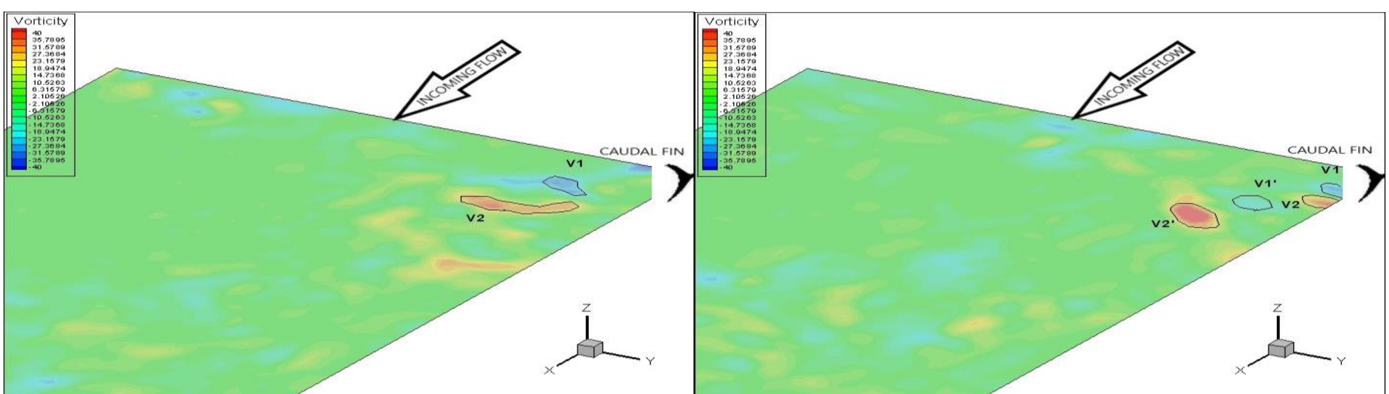


Figure 30: Vorticity V1 & V2 (RE-6200 & 1Hz TBF)

5.2.2 Results AT RE8700 & 1HZ TBF



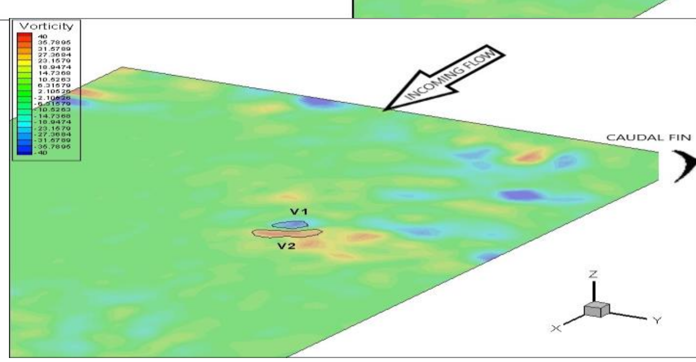


Figure 31: Vorticity V1 & V2 (RE-8700 & 1Hz TBF)

5.2.3 Results AT RE11000 & 1HZ TBF

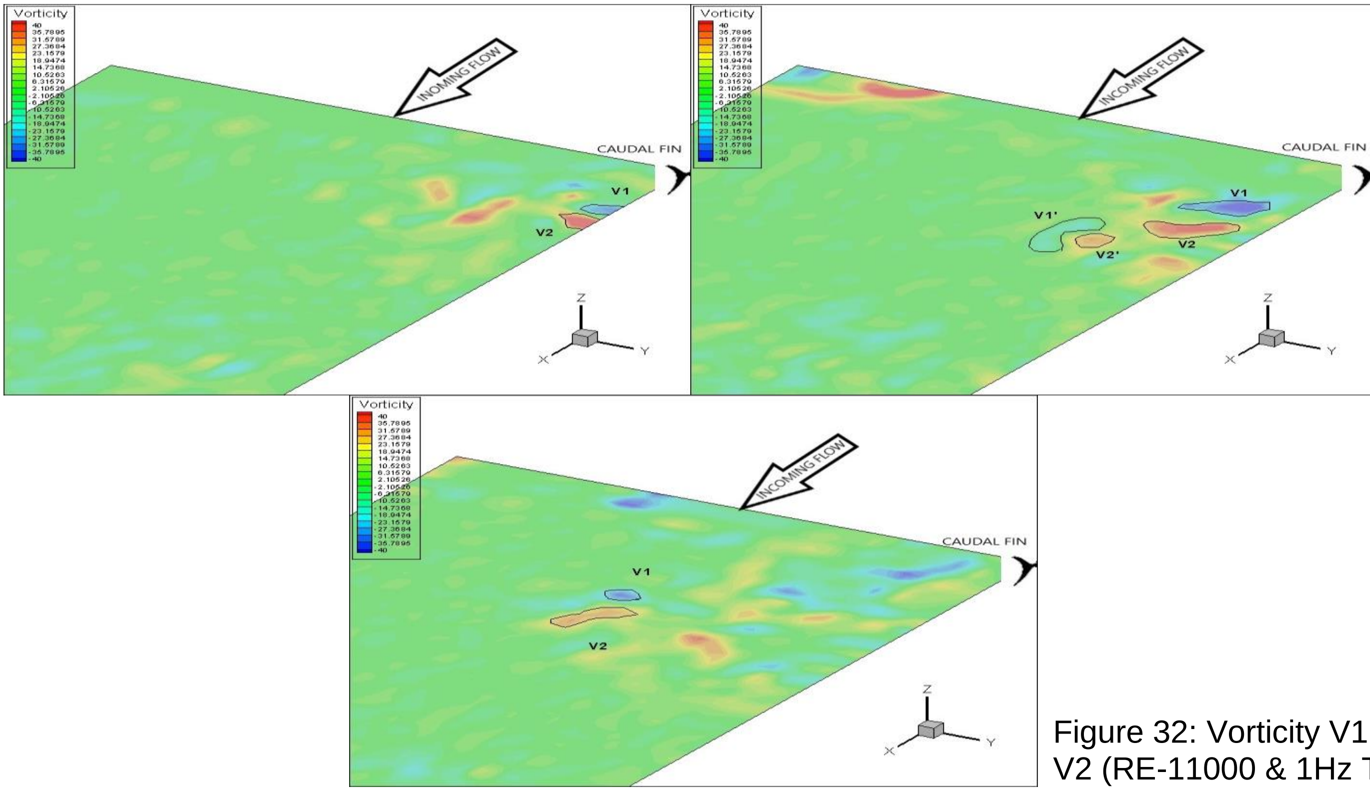


Figure 32: Vorticity V1 & V2 (RE-11000 & 1Hz TBF)

5.2.4 Results AT RE6200 & 1.5HZ TBF

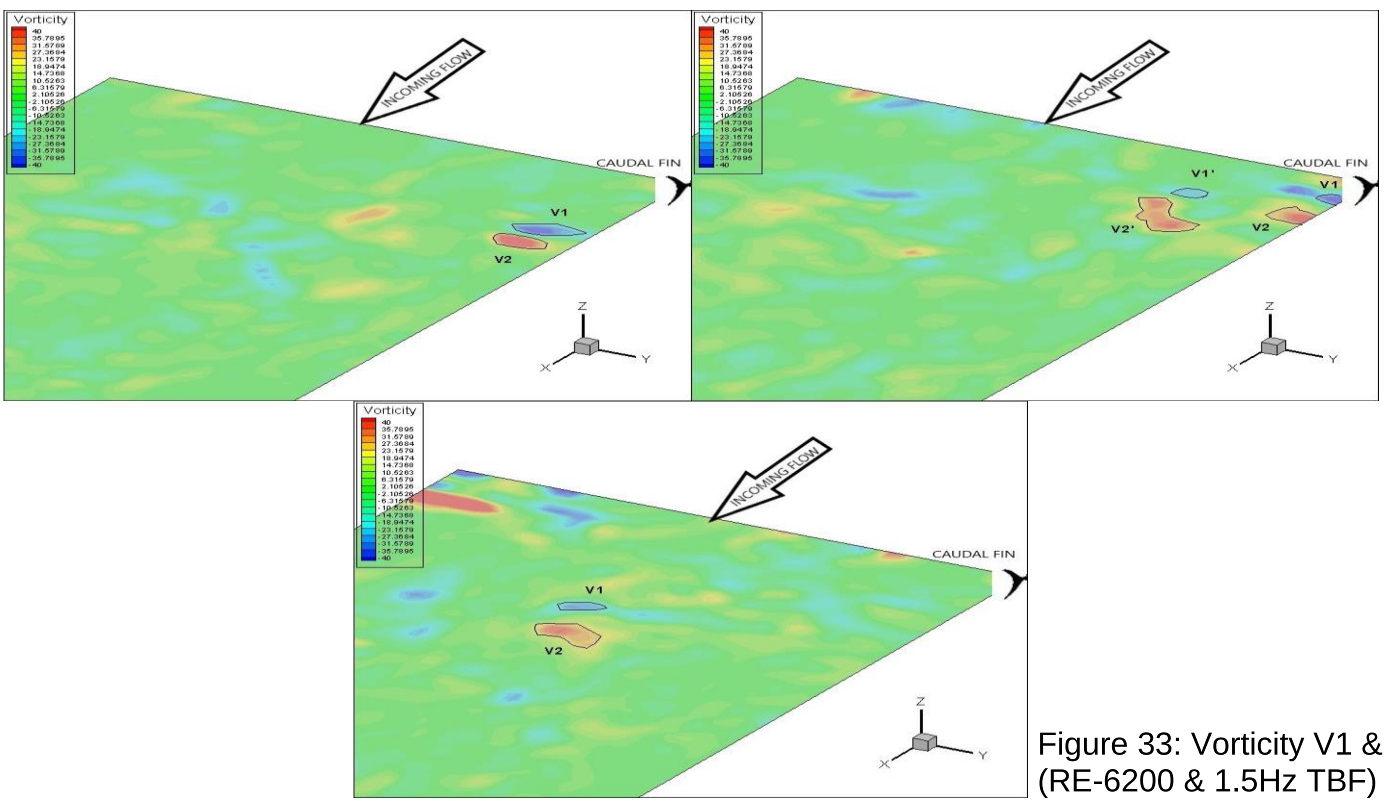


Figure 33: Vorticity V1 & V2 (RE-6200 & 1.5Hz TBF)

5.2.5 Results AT RE8700 & 1.5HZ TBF

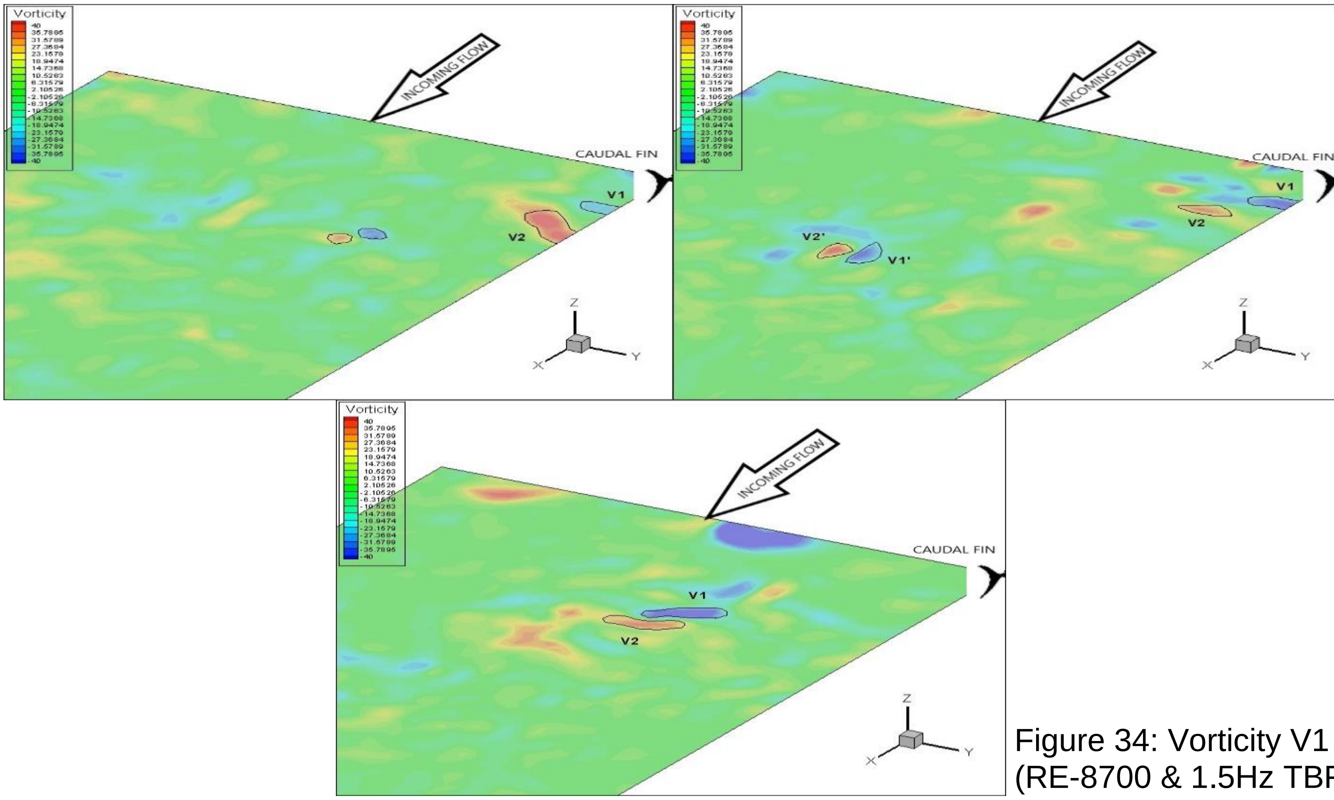


Figure 34: Vorticity V1 & V2 (RE-8700 & 1.5Hz TBF)

5.2.6 Results AT RE11000 & 1.5HZ TBF

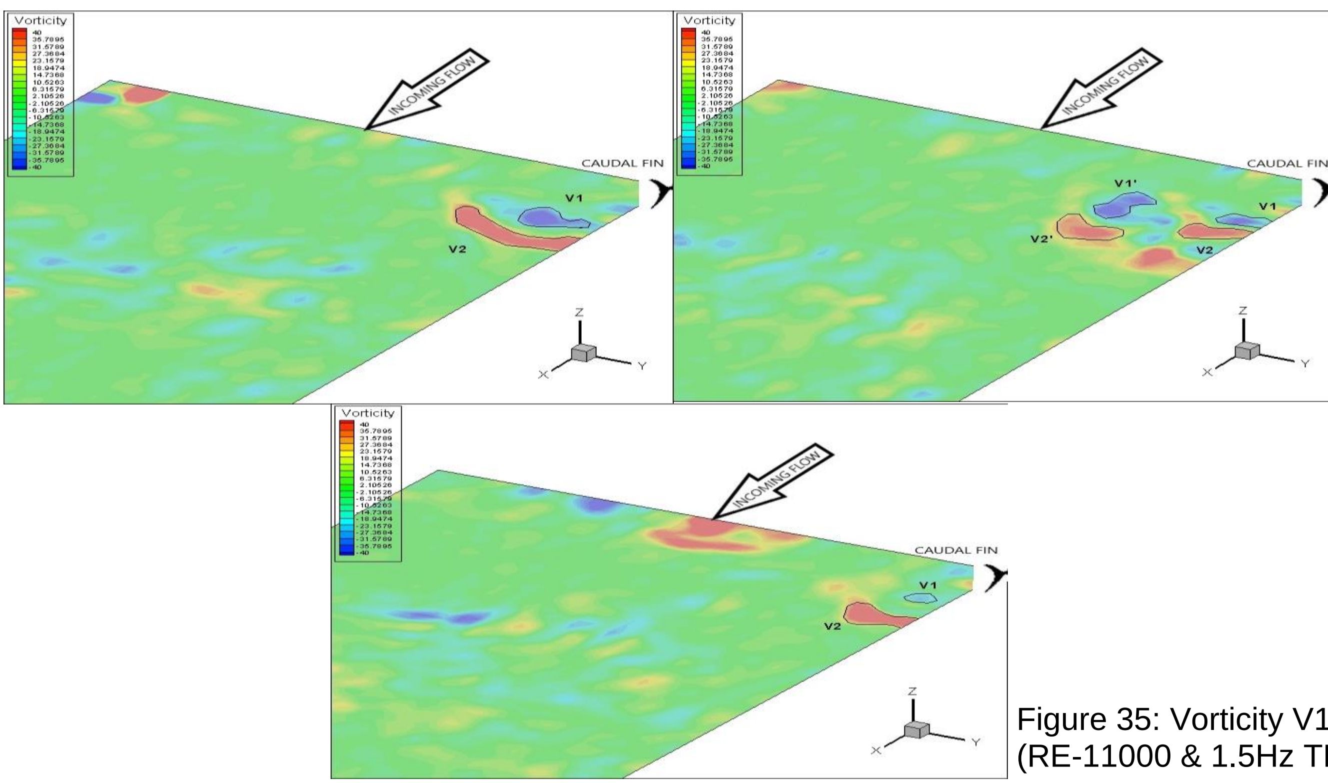


Figure 35: Vorticity V1 & V2 (RE-11000 & 1.5Hz TBF)

5.2.7 Results AT RE6200 & 2HZ TBF

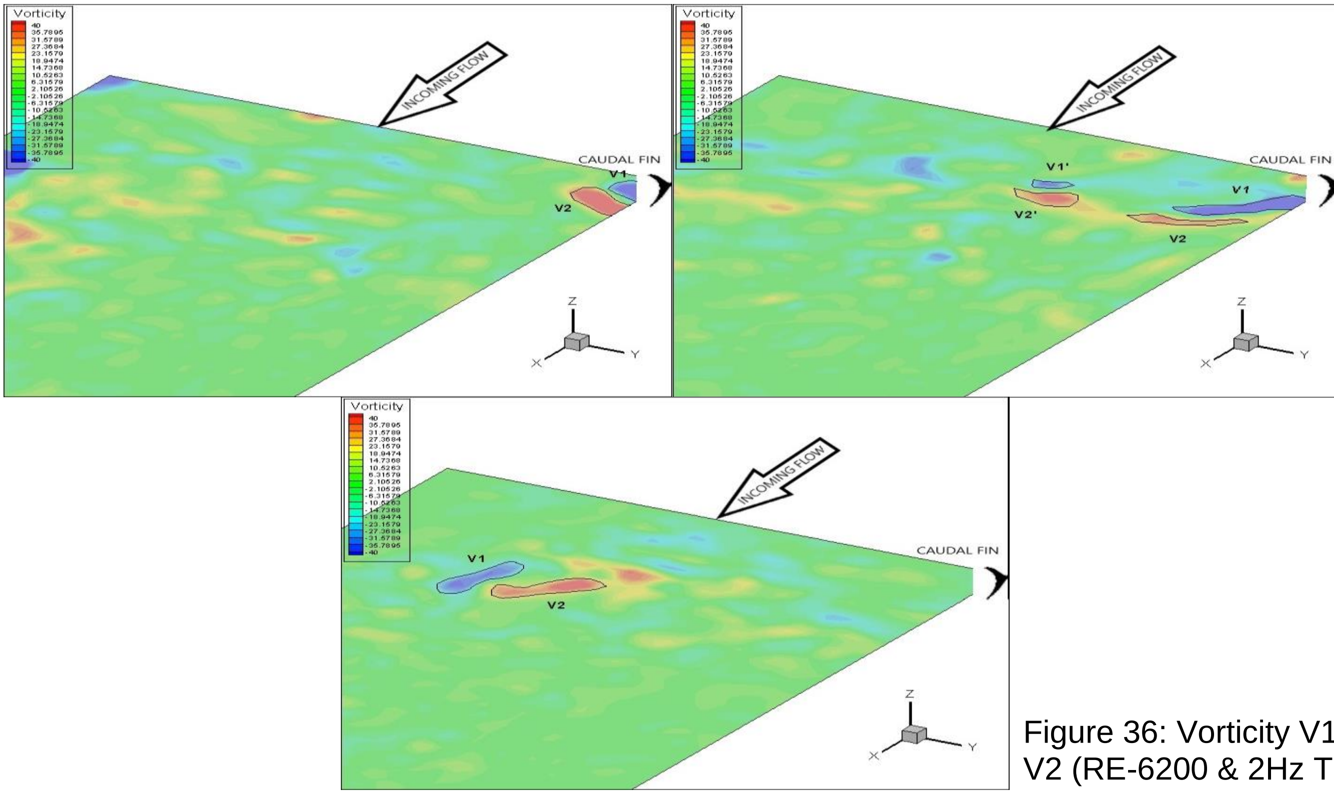


Figure 36: Vorticity V1 & V2 (RE-6200 & 2Hz TBF)

5.2.8 Results AT RE8700 & 2HZ TBF

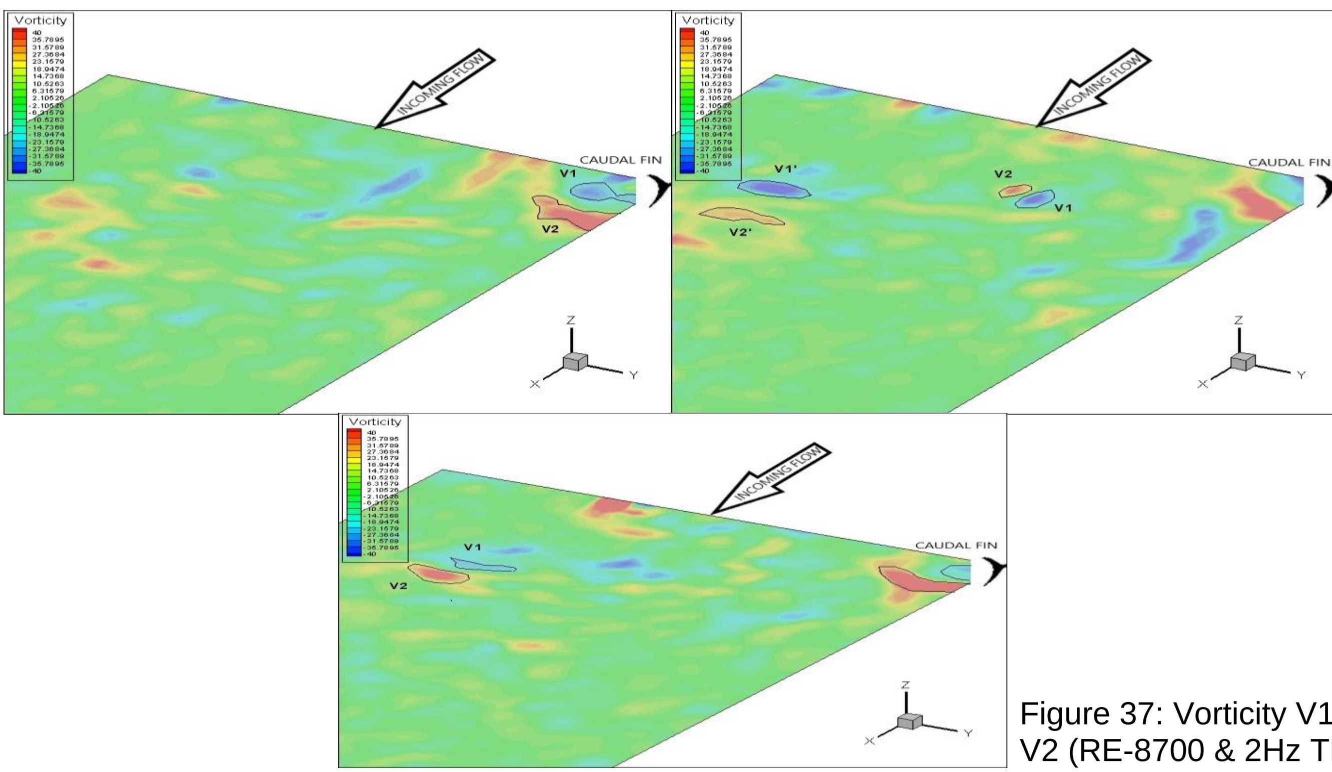
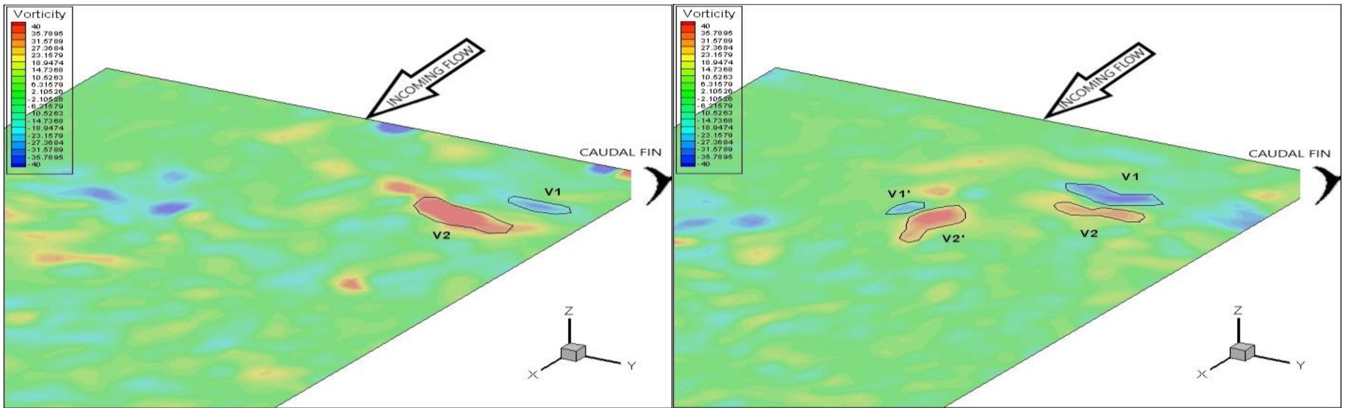


Figure 37: Vorticity V1 & V2 (RE-8700 & 2Hz TBF)

5.2.9 Results AT RE11000 & 2HZ TBF



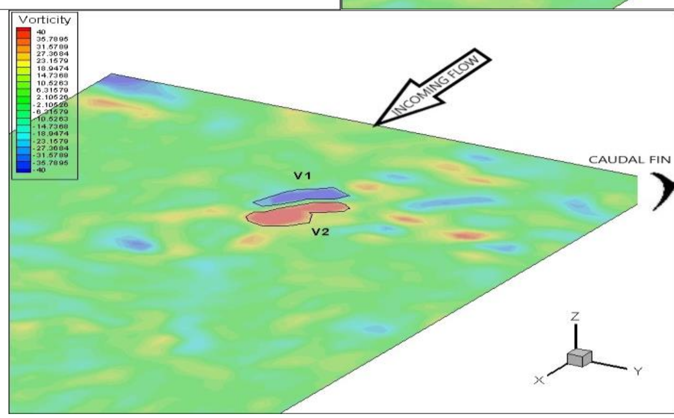


Figure 38: Vorticity V1 & V2 (RE-11000 & 2Hz TBF)

Findings:

1. The higher the tail beat frequency and higher the Reynolds number more elongated will be the vortex hence travelling lower distances in streamwise direction and hence results in lower hydrodynamic efficiency.
2. Single fish analysis is done in which caudal fin is placed at one end of 140mm*80mm grid, and hence the generation of V1 & V2 is seen via PIV, which correlated the obtained results with feng et.al.
3. Experimentation is performed for 3 tail beat frequencies and 3 Reynolds number.
4. Vorticity range is to be set at (-40 to +40) in Tec plot 360 software.
5. Vortices generated at caudal fin of flapping Tuna fish travel in downstream in wedge shape, proving the hydrodynamic advantages of fish school.
6. For every PIV case vorticity is plotted at 3 different instances, first on vortex generation at tail, then the propagation in streamwise direction and last on the vortex before damping or dissipation due to viscous inertial forces of flowing fluid

Conclusion:

In this experimental study, we find out that higher the tail beat frequency & fluid flow velocity (Reynolds Number), result in the smaller vortex size and hence lower propagation is seen in both x and y axis. For single fish cases, best hydrodynamic advantages (58%), are seen at lower tail beat frequency & Reynolds number 6200. Low hydrodynamic advantages of (26%) are seen for both vortex size and vortex velocity at 2Hz tail beat frequency & Reynolds number 11000, for single fish case. Distance larger than 120mm (1fish-length) in side-by-side case would results in lower hydrodynamic efficiency (10%). Better hydrodynamics (54%) are seen at 2Hz tail beat frequency and Reynolds number of 6200 for side-by-side case in synchronous mode of locomotion. Whereas in asynchronous mode of locomotion better efficiency (30.97%) is achieved at 1Hz tail beat frequency and Reynold number of 6200. In synchronous mode of locomotion, vortex propagation is better than in asynchronous, where destructive coupling of V1 and V3 results in lower efficiency. For Reynolds number greater than 6200 better hydrodynamic advantages (54.818%) are seen at 1.5hz tail beat frequency for single fish case. Wake region have influence at 1 fish length, after that vortex are dissipated. Better hydrodynamic advantage means better propulsion with less muscle movement hence raising body temperature of fish to minimum extent, results in lower oxygen consumption to travel longer distances, when move in school. Tuna belongs to Thunniform section of BCF propulsion, which have better propulsion abilities but bad at maneuvering and the reason is the elongated V2 at the end of Stroke-1, which is jet flow in backward direction, becomes a cause for faster propulsion. The overall finding of this study is that the shape of the fish is a very critical aspect along with the tail beat frequency, flow velocity and aspect ratio of caudal fin. Recently researchers are trying to have energy efficient propulsion system for marine transportation to reduce the cost of transport and better propulsion is also needed for deep sea exploration in the development of unmanned underwater vehicles, so that they've biomimetic propulsion thus less aquatic interference is produced.

RECOMMENDATIONS FOR FUTURE SCOPE OF STUDY

1. In future studies, flapping mechanism would be install inside silicone molded fish.
2. Moreover, the movement of fins would also be accounted in research.
3. 3D PIV, Stereo PIV, DPIV or LDV would be used to have better resolution and results.
4. Frictionless towing carriage should be used to find thrust, drag etc.
5. Detailed numerical simulation by incorporating different Reynolds number & tail beat frequencies.
6. A hotwire anemometry test should be performed to measure hydrodynamic forces & Shedding Frequency.

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