Hydrodynamics of multiple fish in staggered arrangement

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Shiraz

Students Signature

Muhammad Shiraz Naeem

MSME-19-320094

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I am thankful to my Maker Allah Subhana-Wattala for guiding me all through this work. at each step and for each modern thought which You set up in my intellect to move forward. In fact, I seem have done nothing without Your invaluable offer assistance and direction. Whosoever had influence on me all through the course of my proposition, whether my guardians or any other person, was Your will, so in fact none be worthy of laud but You.

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Dedicated to my exceptional parents and adored siblings whose tremendous support and cooperation led me to this wonderful accomplishment.

Abstract

Research has been conducted to study the impact of wake vortices, which are the flow pattern effects caused by the movement of one flapping fish, on the thrust of another flapping fish located behind it in a staggered or tandem configuration. The objective of the experimental analysis is to gain insights into the hydrodynamic performance of fish, including the structures of their wakes and shedding vortices. Specifically, this study focuses on staggered and tandem fish configurations. The team has developed 3D printed fish, such as Tuna and Goldfish, which can flap their tails with variable frequencies controlled by a mechanism. The researchers will observe the hydrodynamic effects of two fish swimming in various real-life configurations and analyze the fluid dynamics associated with multiple fish movements. The study will also investigate wake and disturbance analysis in relation to other fish and the environment. Through hydrodynamic analysis, we can gain a deeper understanding of the tandem and staggered behaviors of fish in relation to different frequencies of tail movement and water tunnel velocity.

Key Words: *Vortices, hydrodynamic analysis, frequency, tuna fish*

Table of Contents

List of Figures

List of Tables

CHAPTER 1 INTRODUCTION

This thesis relies on the implementation of a PIV (Particle Image Velocimetry) system to conduct experiments on two distinct mechanical flapping Tuna fish arranged into different real-world positions to Investigate the production and subsequent impact of vortices. A transparent test section in a water tunnel has been utilized to experimentally observe and interpret the movement of particles around the pliable body of a Tuna fish, with the assistance of a camera.

1.1 Background, Scope, and Motivation

Over the last two to fifteen years, considerable research has been conducted in biomimicry, specifically focusing on water, air, and space. These studies aim to uncover the most effective hydrodynamic designs and energy harvesting techniques using mechanical fins and eels. The goal is to delve further into the fluid dynamics realm by analyzing wake structure, vortex shedding, and the formation of leading and trailing edge vortices, as well as aerodynamic and hydrodynamic characteristics, yielding structures with improved design, energy harvesting methods, and flapping propulsion systems. These plans are subsequently implemented in aerial, celestial, and aquatic settings to yield superior outcomes, enduring demanding environmental circumstances. Extensive research has been conducted on the motion of fish and the functionality of their fins, which is carefully observed in live fish to evaluate the effectiveness of their fins. Additionally, the interaction between different fins in different real-life maneuvering situations is also analyzed. To understand the mechanics of fish locomotion, scientists are turning to the creation of robotic fish that mimic natural movement. By doing so, they hope to investigate the hydrodynamics involved designs and solve the mystery of how fish maneuver through water [I]. Every test has advantages and disadvantages unique to itself. Our model proposal involves using a mechanical system that imitates the movement of Tuna fish and comprises of motors, gears, and racks. A silicone-cast fish is mounted on one end of a rotating rod. The hydrodynamics of Tuna is investigated using PIV instrumentation.

Everyday instances of biomimicry comprise of the beak-shaped bullet train design after a bird, the swimmer's suits taking inspiration from the hydrodynamic advantage of a shark's skin and its V-shaped scales, enabling less drag than regular suits encountering greater drag due to Fluid-Solid Interaction, and the plant-based bonding which led to the creation of Velcro.

Nature-inspired designs known as bio-mimics surpass traditional human designs due to their ability to endure rigorous conditions evaluated by nature, resulting in enhanced efficiency compared to human designs.

1.2 Fish forces and their affect

The key features of fish movement, including its reliance on water as a medium, are closely tied to the properties of this fluid, including its high density and resistance to compression. Even small movements of fins or other localized disturbances can have a significant impact on the surrounding environment, due to the extreme density of water compared to air. However, the bodies of marine animals are adapted to this environment and can counterbalance the effects of external forces on the fish. Movement is propelled by fins, and the force required for this action can be generated by either short or long fins. The perpendicular measurements of fins in relation to the flow are referred to as span, while those that run parallel to the water flow are known as chords.

Viscous/friction Drag primary cause can be attributed to the resistance produced by the boundary layer formed by water in contact with the surface of the fish. The wet region's characteristics, the velocity of the fish, and the influence of the boundary layer on fluid movement are all factors that must be considered.

Vortex/induced drag occurs in fish because of their muscular movements that displace water. This displacement creates a force that the fish encounters as drag, which is heavily influenced by the shape of their fins. Additionally, the creation of vortices by the fins results in energy loss that contributes to the drag experienced by the fish.

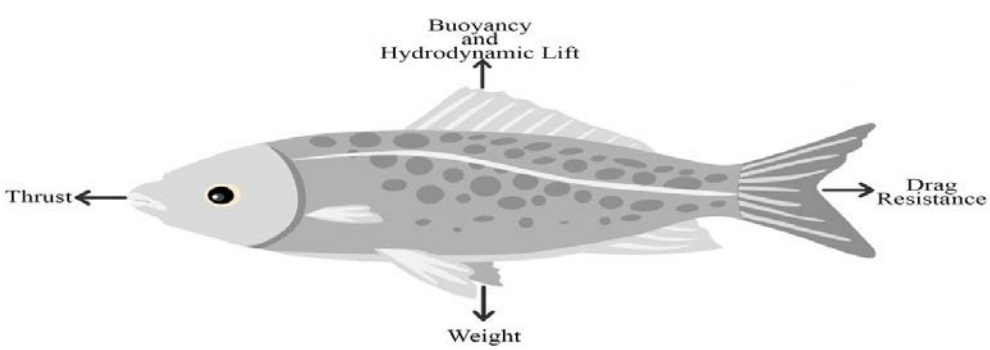

Figure 1 Fish Drag

1.3 Swimming Locomotion

The movement of fish can be distinguished into swimming and non-swimming categories. There are several forms of locomotion considered as non-swimming, such as jumping, flying, gliding, burrowing, and using jet propulsion. On the other hand, swimming is grouped into two categories: periodic and transient movement.

Periodic Swimming, also known as consistent swimming, involves repeating propulsive motions in a cycle. This type of swimming was adopted by fish as a means of traveling over long distances at a uniform speed.

Transient Swimming, also called unsteady swimming, is a quick and agile technique characterized by swift movements, sharp turns, and evasive maneuvers. Typically utilized for evading predators or capturing prey, this type of swimming lasts only a fraction of a second.

1.4 Fish 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 travel 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 function as a source for fish locomotion. Different fish have different fins ranging from pectoral to caudal fins. There are two kinds of motion exercise by fish, Body/Caudal Fin (BCF) locomotion & Median/ Paired Fin (MPF) locomotion. 85% of the fish belong to BCF locomotion families. 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.

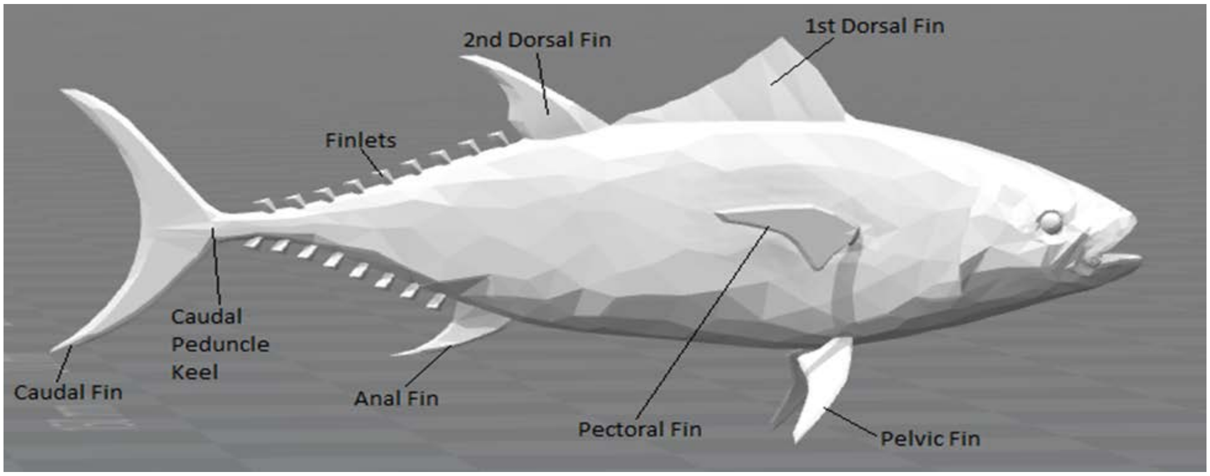

Figure 2 Fins on a Fish

1.5 Body/Caudal Fin Locomotion

Most of the fish swim by producing turbulent oscillations that travel across the body and reach caudal fin, which in turn is the force required for locomotion. This type of locomotion is termed as Body/Caudal Fin locomotion (BCF), swimming using these body structures includes anguilliform, sub-carangiform, carangiform, and thunniform locomotory modes, as well as the oscillatory ostraciiform mode. BCF is the most efficient locomotion and has higher cruising speeds maintained for prolonged periods.

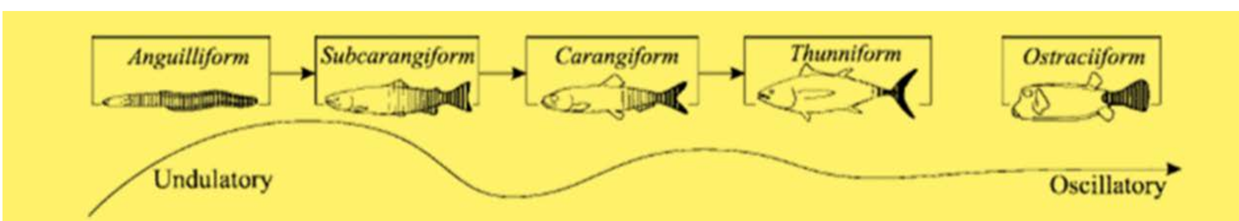

Figure 3 BCF locomotion

1.5.1 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 that belong to this mode can swim forward or backwards depending upon the direction of propulsive wave.

1.5.2 Subcarangiform

This type of mode is quite like anguilliform fish mode but except for fluttering is limited anteriorly thus by increasing in half of the fish posterior.

1.5.3 Carangiform

This type of mode is even faster than anguilliform and subcarangiform by restricting its turbulence to one third 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.

1.5.4 Thunniform

This type of locomotion is the 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.

1.5.5 Ostraciiform

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

1.6 Median/Pair Fin Locomotion

In this type of swimming median fin or paired fin use a set of muscles to control the movement of fins to move and rotate. Two types of fish locomotion are 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 the advantage of higher maneuverability. Paired fins consist of pectoral and pelvic fins, while Median fins consists of dorsal, caudal, anal, and adipose fins. MPF locomotion is divided into seven categories as follows.

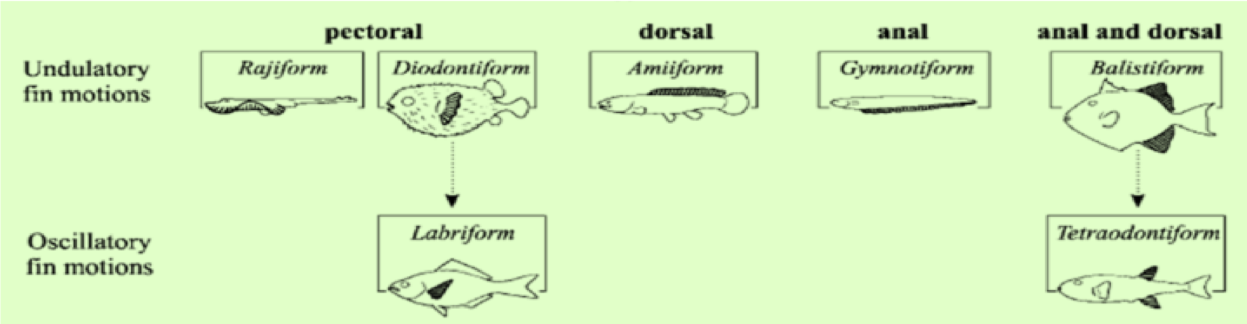

Figure 4 MPF Locomotion

1.6.1 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 a way that they propel by changing fluttering/undulating amplitude ranging from anterior fins to posterior fin.

1.6.2 Diodoniform

This type of swimmer is not 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.

1.6.3 Amiiform

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

1.6.4 Gymnotiform

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

1.6.5 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.

1.6.6 Tetraodontiform

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

1.7 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 is easier than ever to explore the 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 fillets providing effective and efficient locomotion.

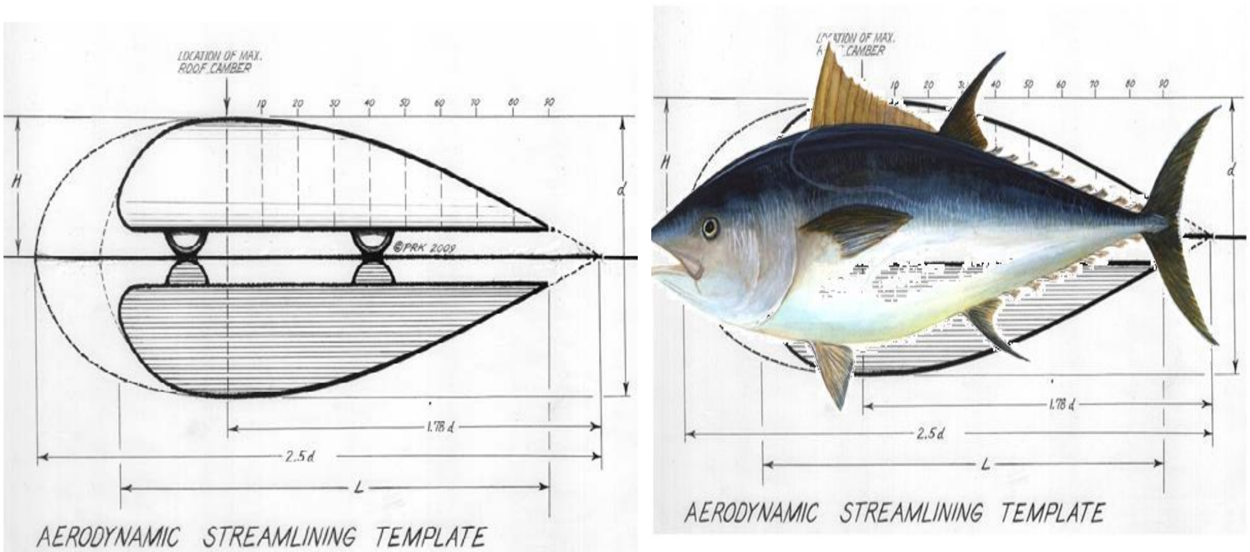

Figure 5 Fish streamline chart

1.8 Scaled Model Analysis

One the basis of 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.

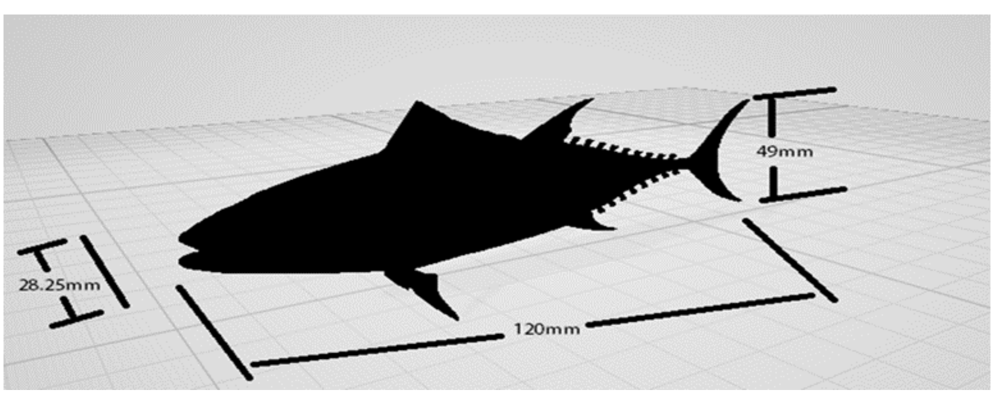

Figure 6 Fish Dimensions

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

Table 1 scaled model analysis.

RESILT: The scale down model is validated via Reynolds number of experimental and real-life conditions and found to be equal.

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.

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.

Mohsen Daghooghi et al. 2015, studied the hydrodynamic pros 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.

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 affect their oxygen consumption by numerically modelling different real-life scenarios to calculate drag acting on fish.

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.

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.

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].

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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 affects their oxygen consumption numerically. modelling different real-life scenarios to calculate drag acting on fish [34].

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Mohsen Daghooghi et al. 2015, studied the hydrodynamic pros 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 GVet 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 conducted 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 V 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 obtained 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 EXPERIMENTAL METHADOLOGY

3.1 DESIGN OF EXPERIMENTS

The experimentation is done at different tail beat frequencies and different Reynolds numbers. Single fish and side by side real life configurations are discussed in this research. Experimentation is conducted at three Reynolds numbers of 6200, 8700 & 11000 and on three tail beat frequencies 1Hz, 1.5Hz & 2Hz. 9 single fish cases are performed and 6 side by side cases are performed on both synchronous and asynchronous mode of locomotion.

Table 2 design of experiments

Cases	Distance	
Tandem	60mm	
	120mm	
Staggard	60mm	60mm
		120mm
	120mm	60mm
		120mm

Other Measurements/variable

- Tail Beat Frequencies= 1-2Hz
- Reynolds Number= 6200

Output to be Measured

- Vorticity
- Vortex Size
- Vortex Velocity
- Distance Travelled

3.2 BLUFF BODY SHAPE

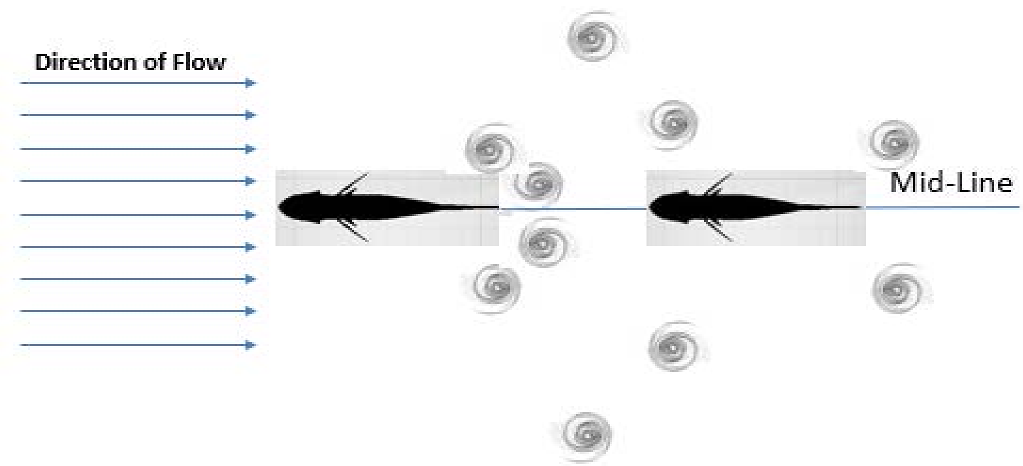


Figure 7 tandem schematics

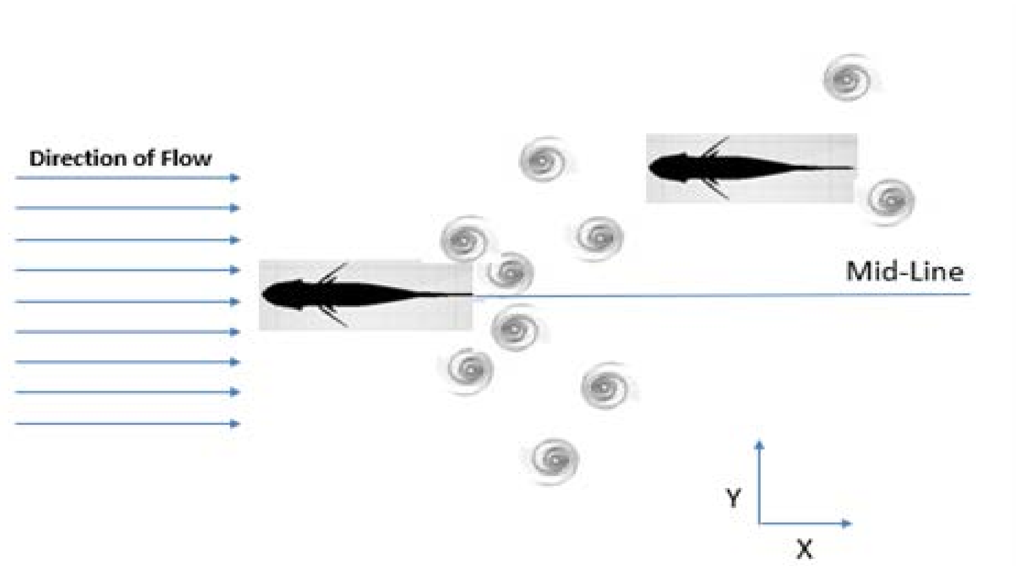


Figure 8 Staggered schematics

3.3 EXPERIMENTATION

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, back and forth motion by using cam, follower and slider technique:

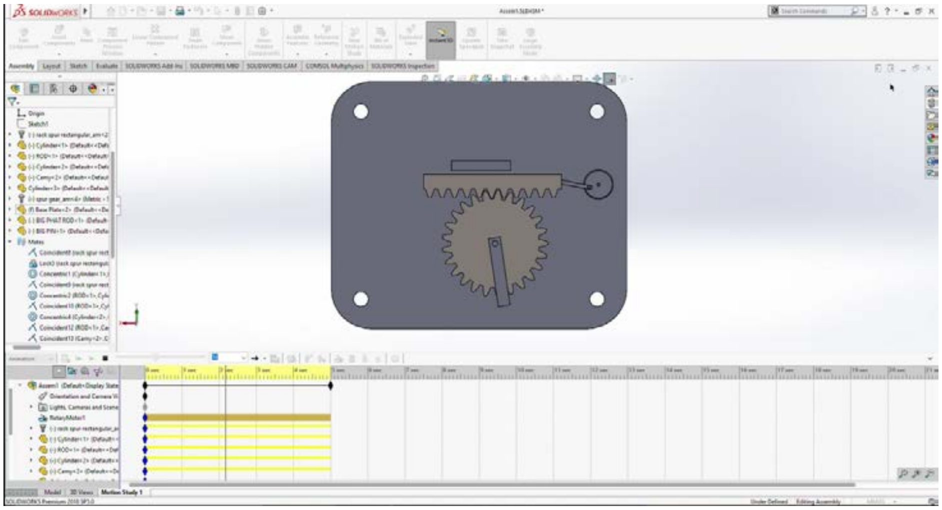


Figure 9 Follower Ans Slider Model

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

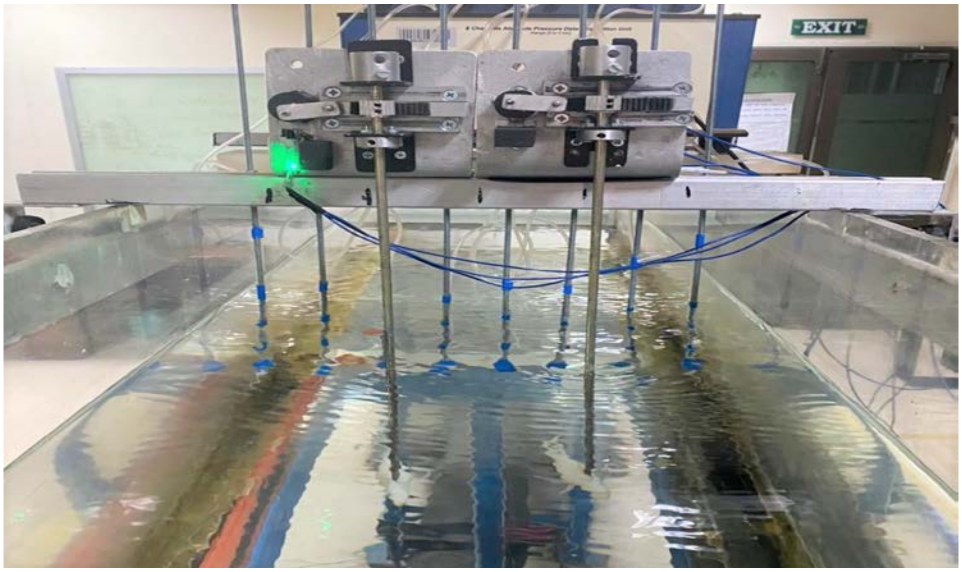


Figure 10 Fish working mechanism.

3.4 Fish fabrication

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

3.4.1 3d 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. The drawback is flexibility cannot be achieved with TPU, also 3d printing is still in developmental phase and hence expensive, we can use SLA printing technique, but facility is not available readily.

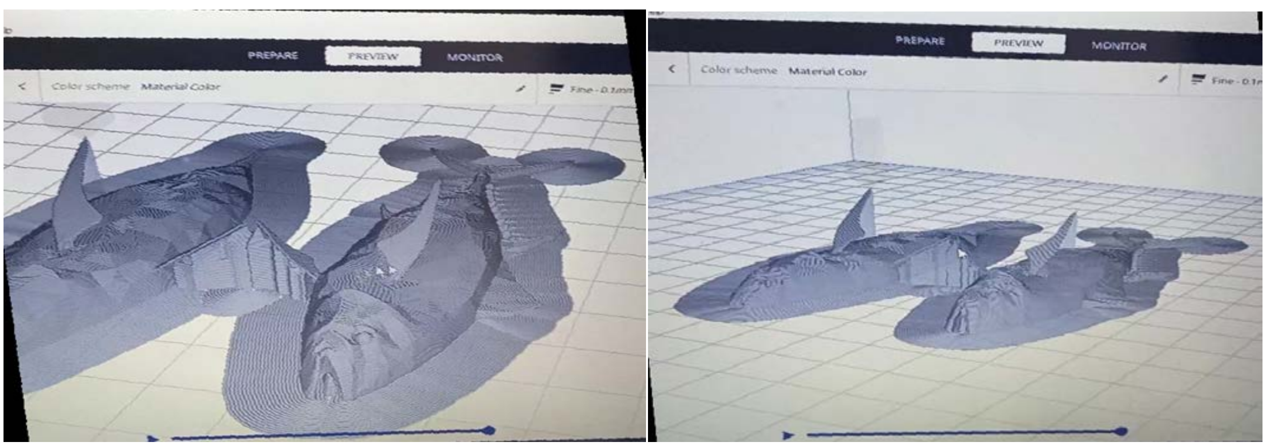


Figure 11 SLA 3D Fish printing

3.4.2 Silicone casting in plaster Paris mold

Firstly, 3d print a fish in 2 halves vertically from grills, and then 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 the plaster of Paris setting time is quite small hence cannot be able to make mold easily.

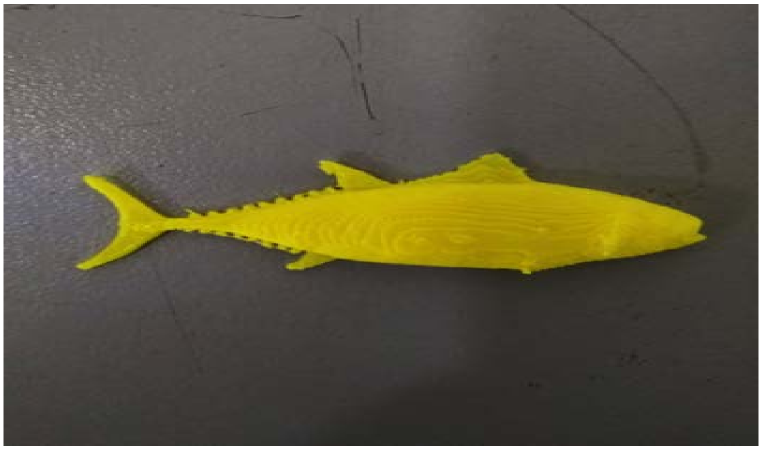


Figure 12 3D printed Fish.

3.4.3 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 great adaptability and great 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. The drawback is fins & scales still cannot be made in mold.

Figure 13 silicon Fish Mold

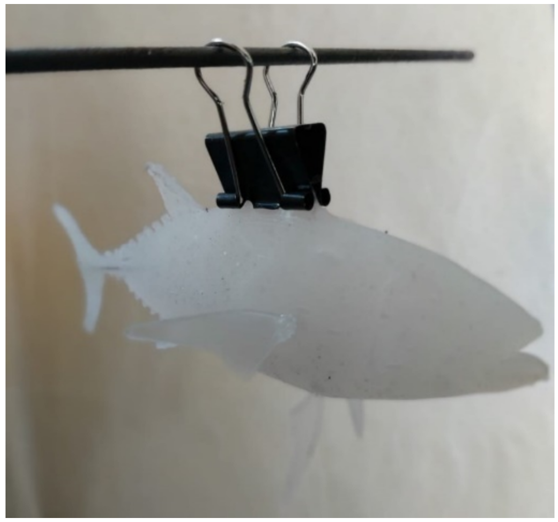


Figure 14 Silicon fabricated Fish

3.5 2nd experimental setup: PIV

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. Laser 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. The camera 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. The required data is extracted from images via MicroVec's software and then stream traces are plotted in plot 360 software is used.

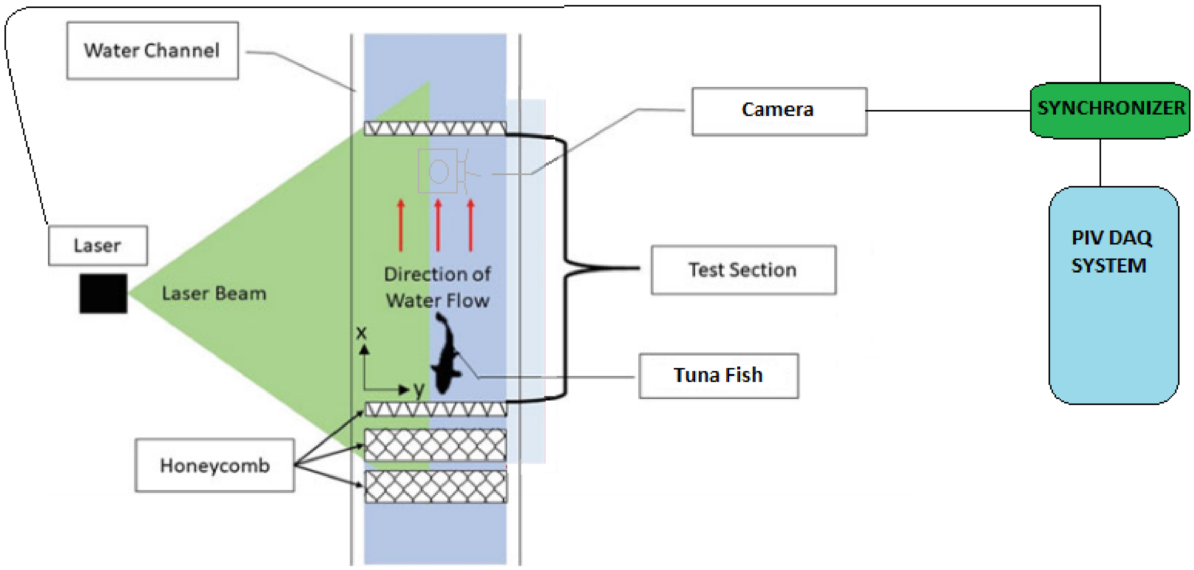


Figure 15 Water Tunnel flow chart

The 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 in the course of time to draw a velocity & vorticity contour, to understand how fluid interact with fish at different tail beat frequencies & Reynold numbers.

Figure 16 SMME Flow Lab

1.Workstation

2. Camera-Laser Synchronizer

3. Laser eye protection

4. MicroVec seed particles for PIV

5. Laser Frequency Modulator

6. Bed laser

7. PIV camera

8. Water tunnel test section

CHAPTER 4 RESULTS AND DISCUSSSION

4.1 Image J Results

The results driven from the experimental set up all of basically of two types which contains 2 software's oh Tec plot and images J software from the image J software the manual results are derived and note it down and evaluated on the Ms. excel and the final graphs are formulated and the tech pullout results are calculated through visual representation that is generally off vortices shedding that comprises of vortices making propagation and damping and hence a general how to dynamics of multi fish is concluded .

• Process slow-motion HFR video in MATLAB and produce frames.

• Open Image J & define scale in pixel/mm ratio.

• Mark the scale on the 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.

Vortex Size (Area) vs Tail beat frequency

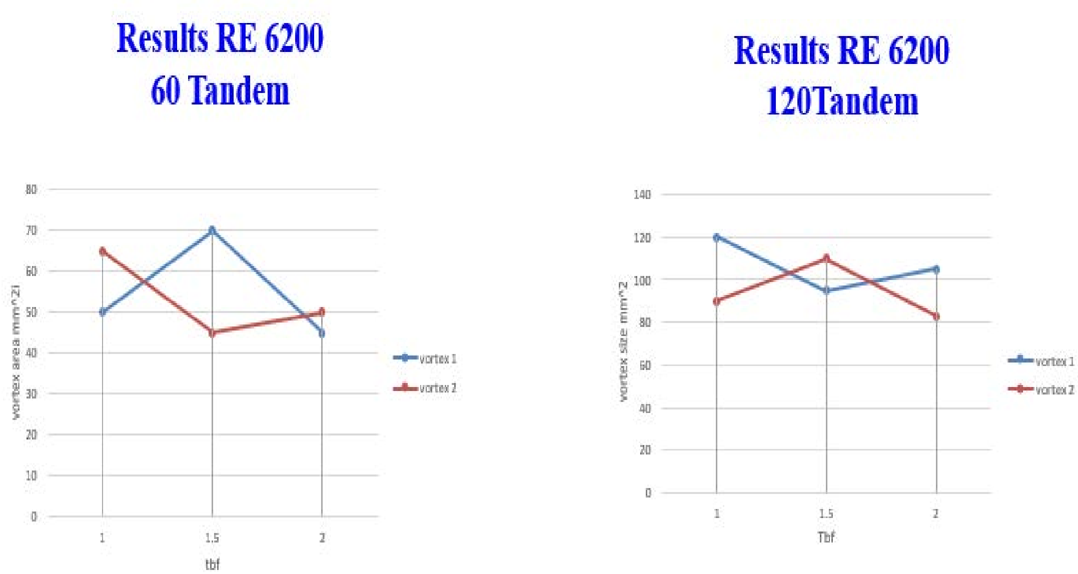


Figure 17 Vortex vs TBF

Figure 17 in the thesis explicitly illustrates the quantitative relationship between vortex size (measured as area) and the tail beat frequency (TBF) of the fish models. The graph shows a clear trend: as the tail beat frequency increases, the size of the vortices created by the fish model's tail decreases. This inverse relationship suggests that faster tail movements produce smaller, but potentially more numerous, vortices. This finding is critical in understanding the hydrodynamic efficiency of fish swimming and has implications for the design of bio-inspired aquatic vehicles where tail beat frequency could be a crucial factor in controlling propulsion and manoeuvrability.

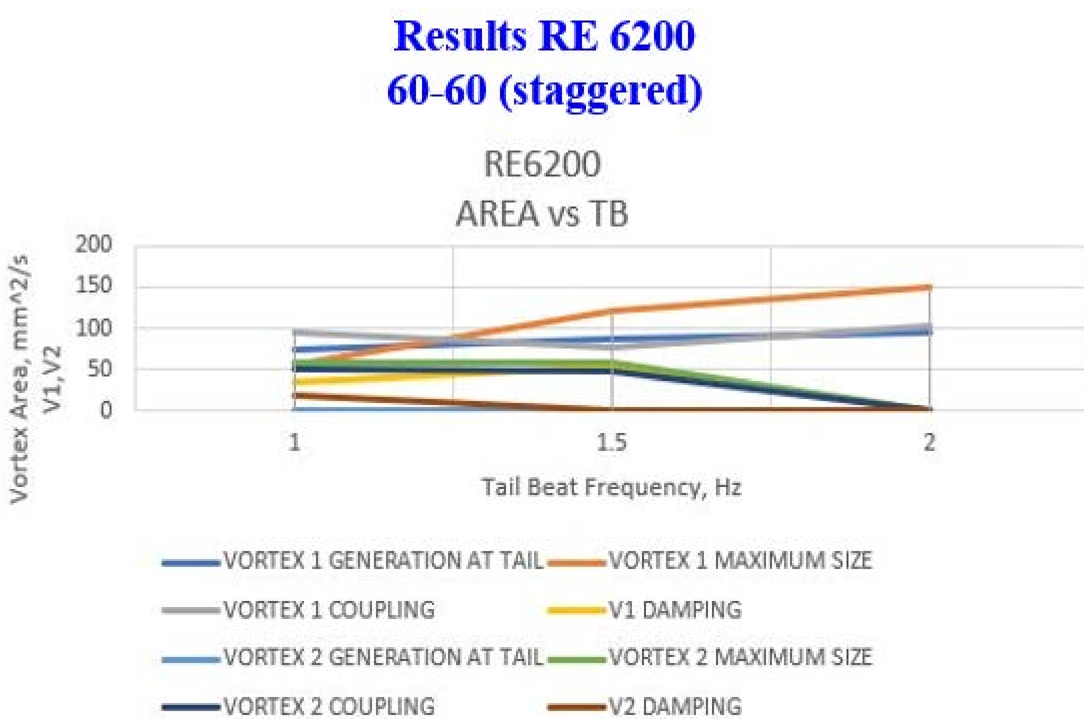


Figure 18 Result RE 6200 60-60

Figure 18 presents data under specific experimental conditions characterized by a Reynolds number of 6200 and a fish model arrangement described as 60-60. This arrangement likely refers to the positioning of two fish models in the experimental setup, possibly indicating a tandem formation with 60 mm separation. The data in this table includes precise measurements such as vortex size, downstream velocity, and wake characteristics under these conditions. The results in this table are instrumental in analyzing how closely positioned fish models in tandem influence each other's hydrodynamic environment, particularly in terms of vortex formation and propulsion efficiency.

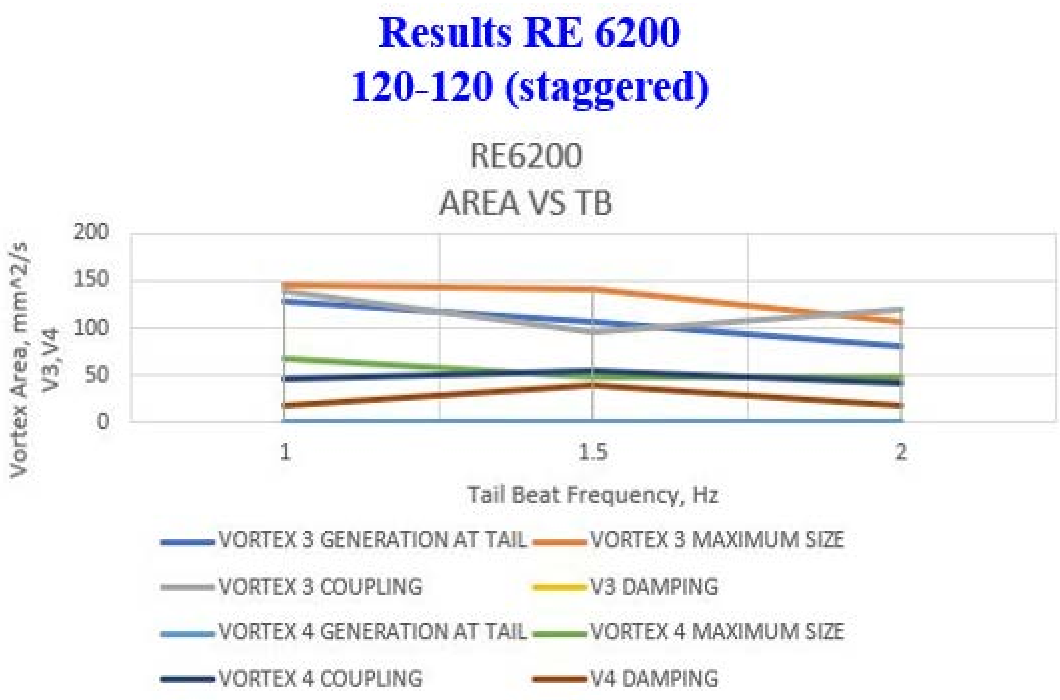


Figure 19 Result RE 6200 120-120

Figure 19 extends the analysis to another experimental scenario with the same Reynolds number (6200) but a different fish model arrangement (120-120). This change in fish model positioning (likely indicating a larger separation of 120 mm) provides insights into how increased distance between tandem fish models affects their hydrodynamic interaction. The data in this table would include variations in vortex dynamics, flow velocity, and wake patterns, compared to the closer arrangement in Table 3. Such comparisons are crucial for understanding the optimal spacing for efficient propulsion in fish schools or bio-inspired robotic swarms.

Results RE 6200
60-120 (staggered)

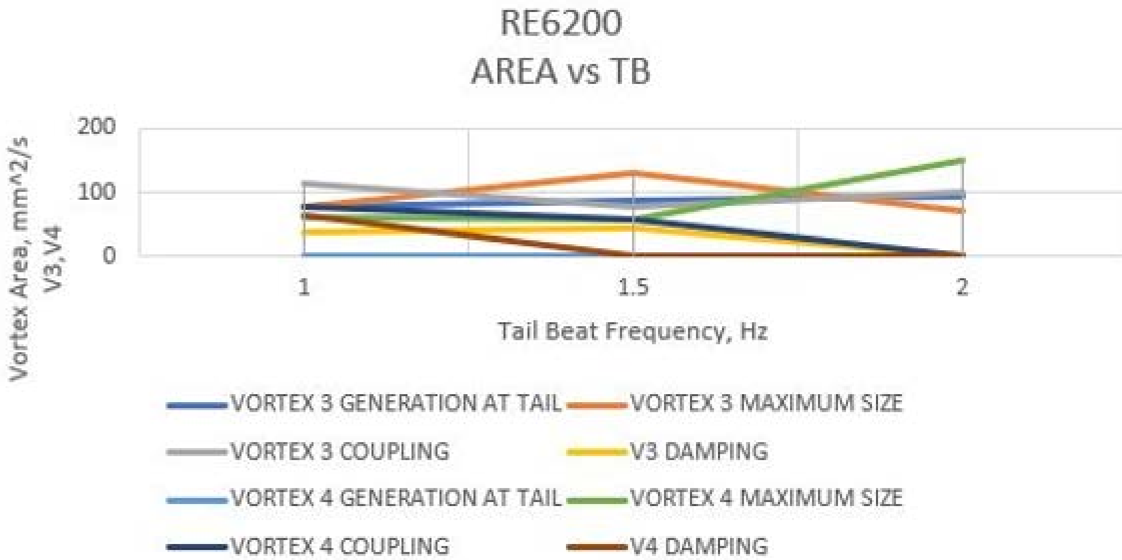


Figure 20 Result RE 6200 60-120

Results RE 6200
120-60 (staggered)

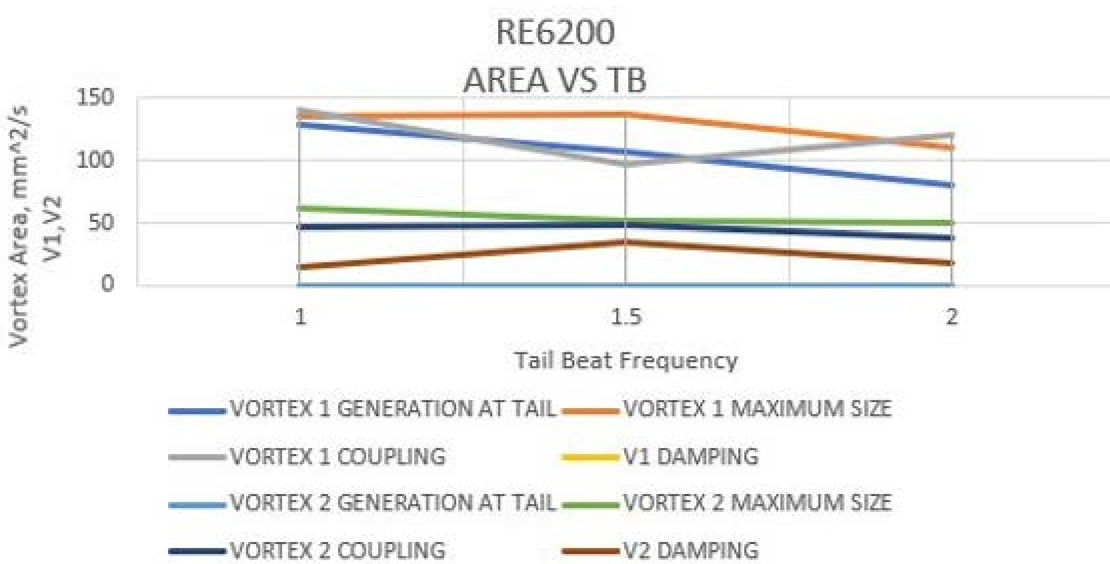


Figure 21 Result RE 6200 120-60

Figure 20 and 21 are the detail the results from experiments where the fish models are placed in staggered formations, with varying distances (60-120 and 120-60 mm) between them. These tables provide a comprehensive look at how staggered arrangements impact the hydrodynamic interactions between the fish models. The variation in distances allows for an examination of how vortex coupling, wake interaction, and flow dynamics differ from the tandem arrangements. This is particularly important for understanding complex swimming formations in natural fish schools and for the development of advanced formation control in autonomous underwater vehicles.

The detailed analysis of Figure 17 - 21 offers significant insights into the complex hydrodynamic interactions in multi-fish systems. These results not only contribute to a deeper understanding of fish swimming mechanics but also have broad applications in engineering, especially in the design of efficient underwater vehicles and systems inspired by biological models. The interplay of tail beat frequency, vortex dynamics, and fish positioning highlighted in these results underscores the intricate balance of forces in aquatic propulsion and energy efficiency.

4.2 PIV Results

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

2nd experimentation is based on 2D PIV.

• Experimental technique of flow visualization is conducted to study wake generated by caudal fin.

• For PIV laser is set at mid of 2nd caudal fin.

• Pulse delay is set at 3000 microseconds.

• The pulse width is set at 2000 microsecond.

• A camera is set beneath the 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 files.

• Then the DAT file is open in Tec Plot 360 Software to find Vorticity.

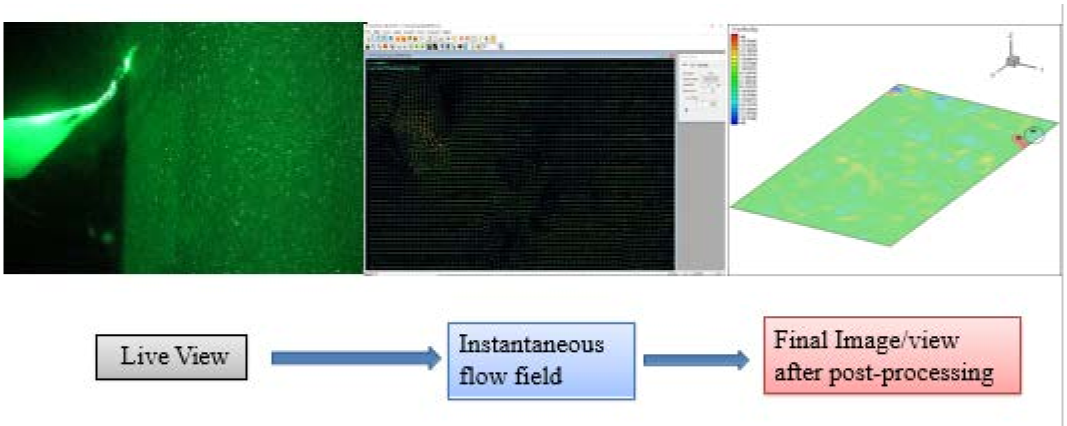


Figure 22 PIV Processing

Figure 23 Fish Testing PIV

Figure 22 depicts the processing methodology or results of the Particle Image Velocimetry (PIV) analysis. The PIV experiment involved using a laser set at the midpoint of the second caudal fin of the fish model. This setup was aimed at studying the wake generated by the caudal fin in a controlled environment. The experiment setup included setting pulse delays and widths for the laser, capturing images from a camera positioned beneath the water tunnel. A total of 1000 images were taken and processed through Micro-Vec's PIV Software, resulting in DAT files. These files were then analyzed using Tec Plot 360 Software to study the vorticity patterns. The figure presents a visual representation of the vorticity patterns obtained from the PIV analysis. This would show the intricacies of wake patterns and vortices created by the caudal fin's motion.

Figure 23 illustrates the setup or the viewpoint of the fish model testing in the experimental setup. This figure depict the arrangement of the fish model within the water tunnel, showing the positioning of the laser, camera, and other instrumentation used in the PIV experiments. It provide a visual insight into how the fish model was placed for the experiments, including angles, distances, and the overall experimental configuration. Understanding the testing setup is crucial as it gives context to the data collected and helps in interpreting the results accurately. This viewpoint would be instrumental in understanding the spatial dynamics and the interaction of the fish model with the induced flow in the tunnel.

These figures, in conjunction with the rest of the thesis, provide a comprehensive look at the hydrodynamic properties of fish swimming, particularly focusing on the wake generation and vorticity patterns. The visual representations and the methodologies detailed in these figures are integral to understanding the complex fluid dynamics involved in fish locomotion and have potential applications in biomimetic designs and aquatic vehicle development

4.2.1 Vortex travelling

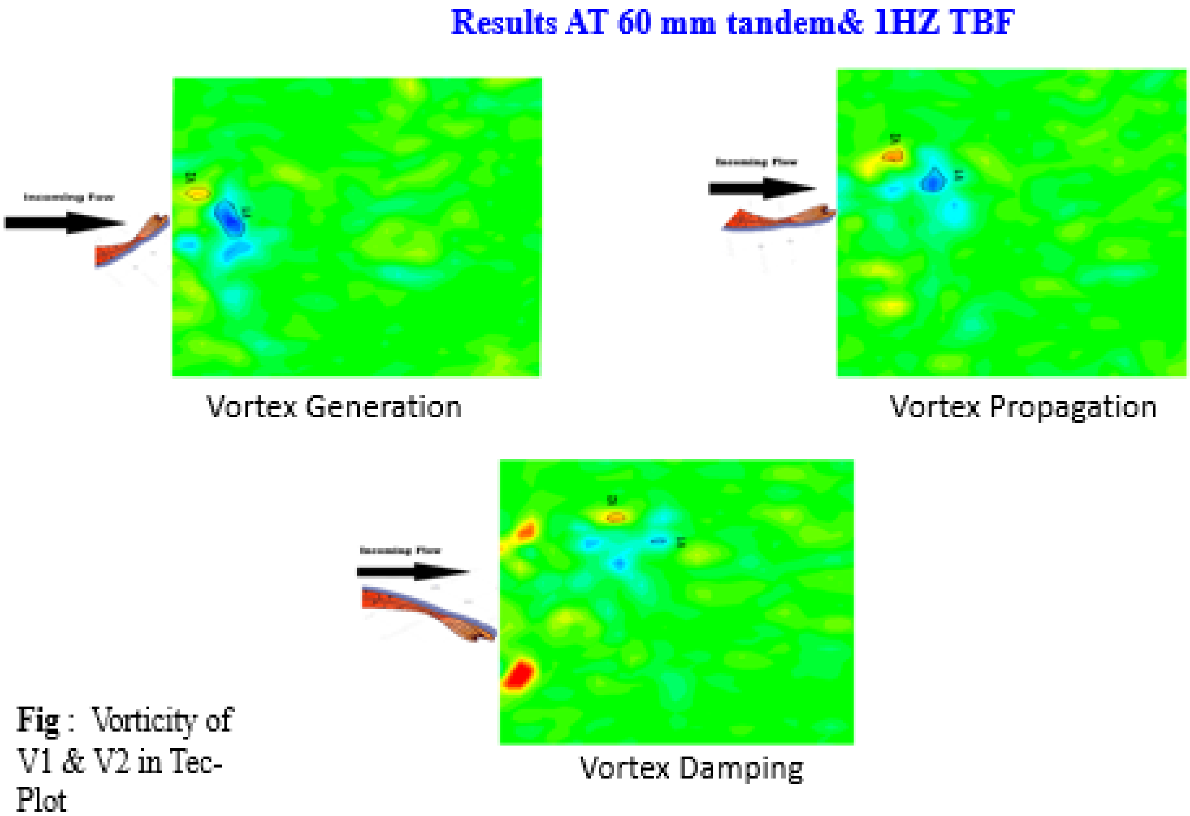
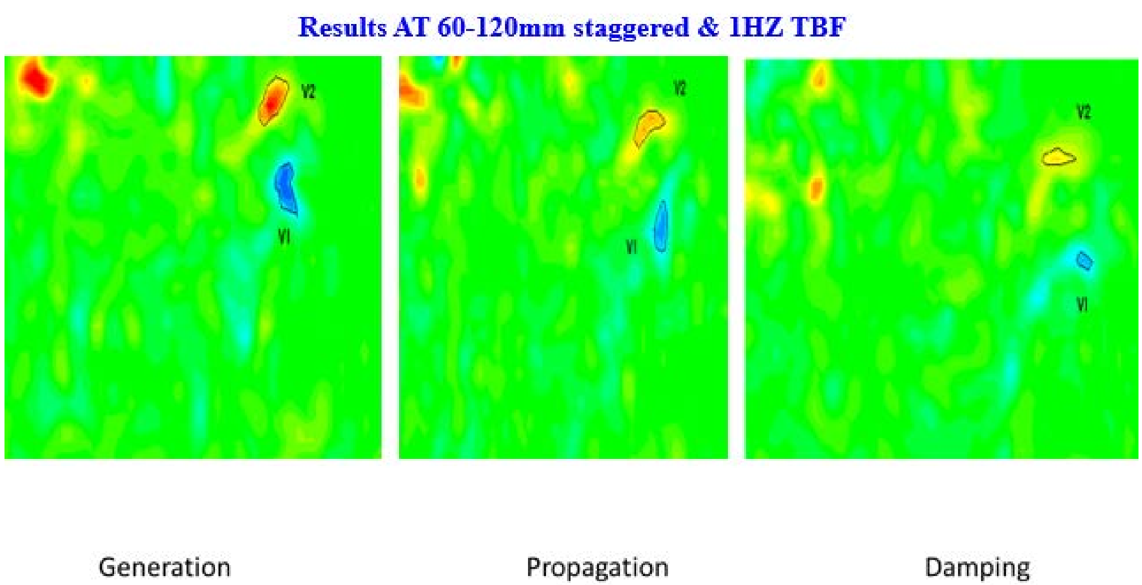
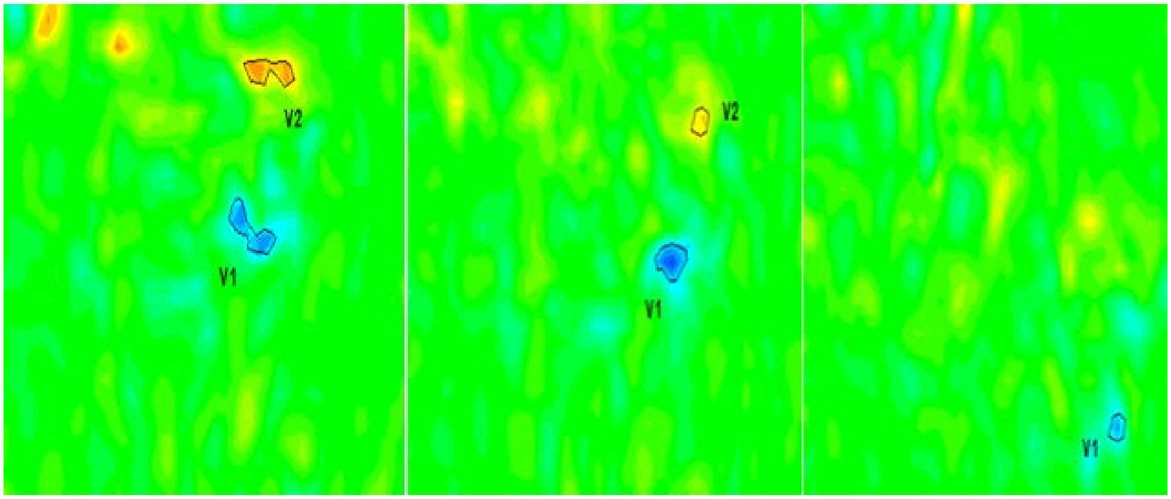


Figure 24 Vorticity of V1 and V2 in Tech Plot



a)

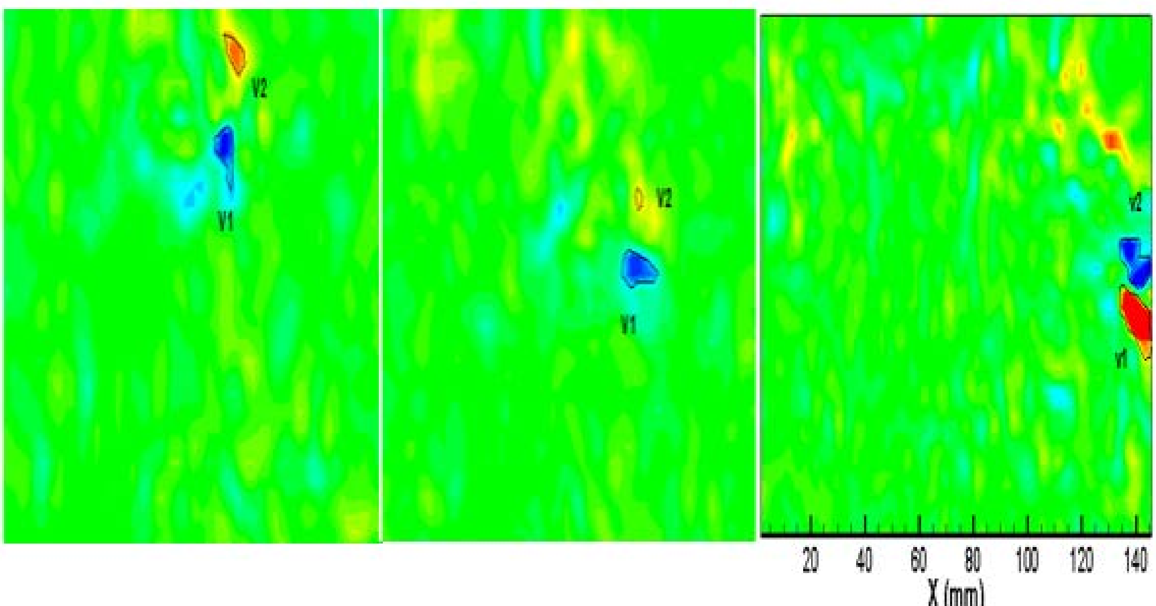
Results AT 60-60mm staggered & 1HZ TBF



Generation Propagation Damping

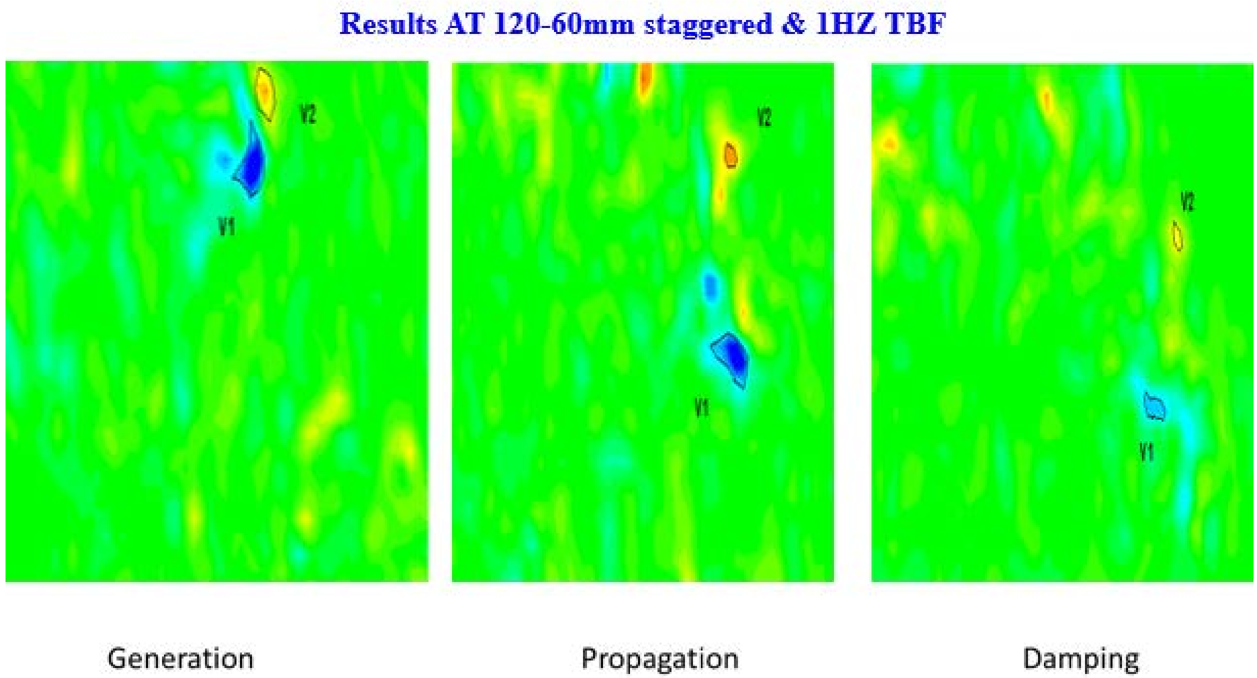
b)

Results AT 120 mm tandem& 1HZ TBF

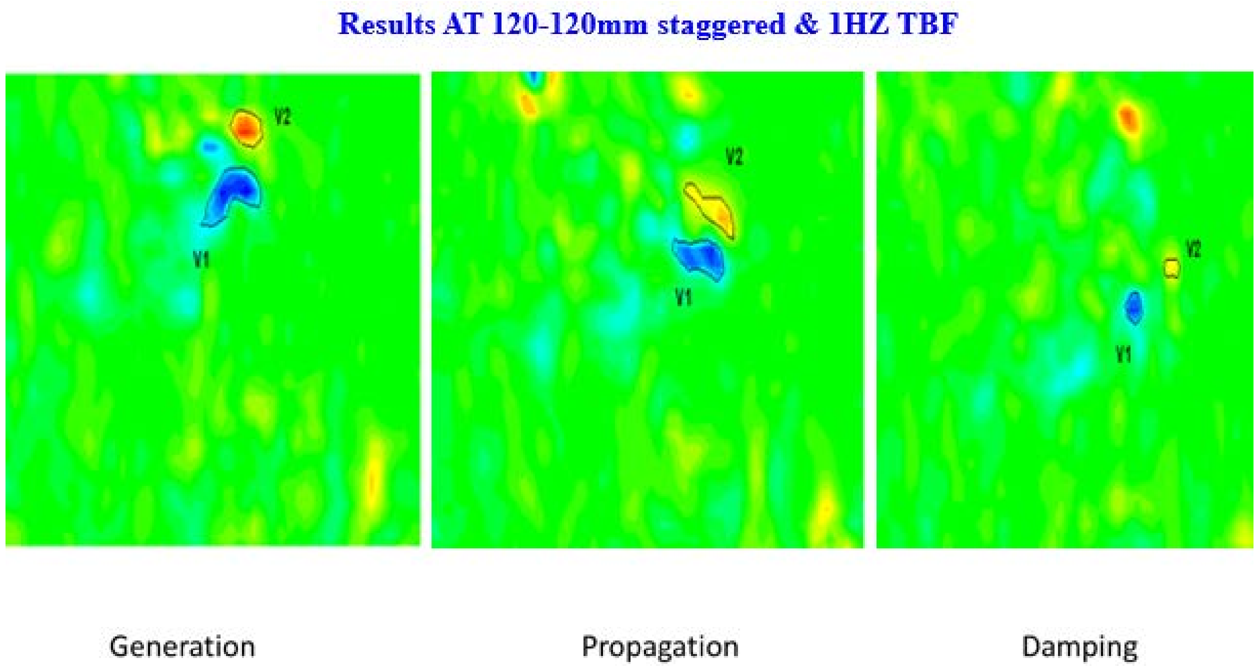


Generation Propagation Damping

c)



d)



e)

Figure 25 Vorticity of V1 and V2 at different gaps

Figure 24 & 25 in the thesis presents the results of vorticity analysis conducted using Tec Plot 360 Software. This figure illustrates the vorticity patterns of two different vortex formations, labeled V1 and V2, which were observed in the wake of the fish model during the experiments. The figure is expected to show detailed vorticity contours or vectors, providing insights into the strength, direction, and distribution of the vortices generated by the fish model's movement. Understanding these vorticity patterns is crucial for analyzing the efficiency of propulsion and the hydrodynamic interactions in fish-like swimming

4.3 Ux velocity (downwash)

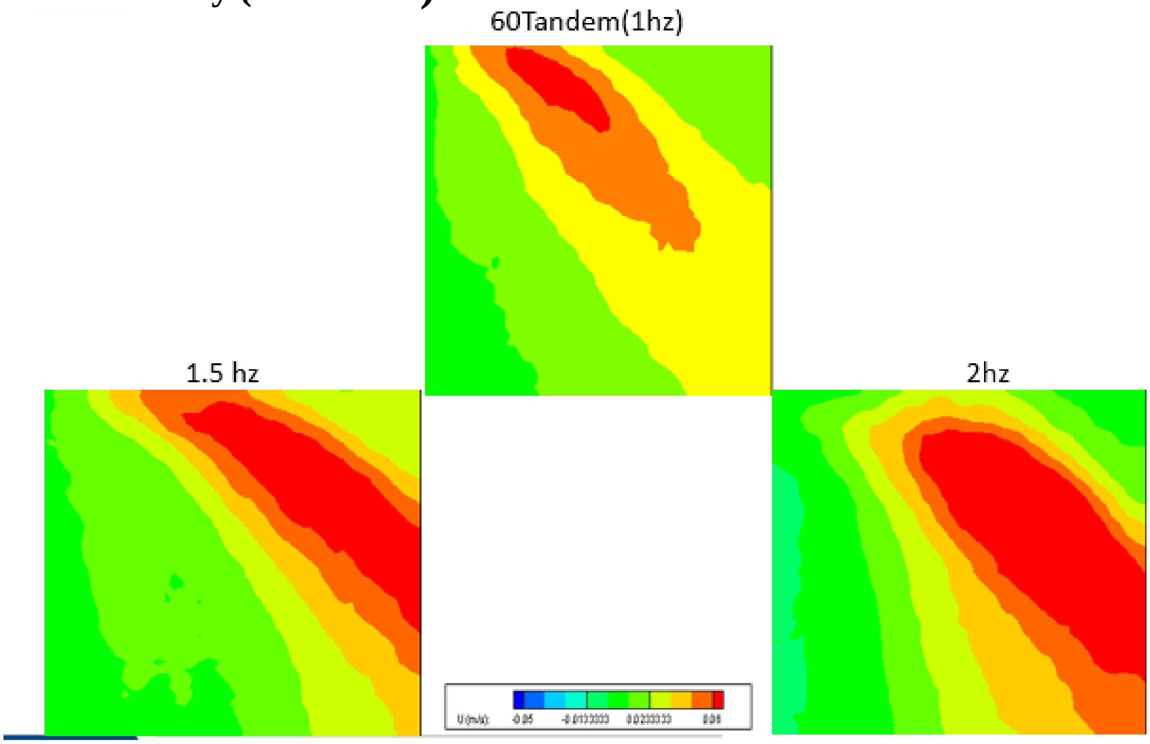


Figure 26 60 tandem Ux

Given the focus on hydrodynamics and vortex analysis in the thesis, Figure 26 depict the Ux velocity (likely referring to the longitudinal component of velocity) in a tandem arrangement of fish models with a 60 mm separation. The figure show velocity vectors or contours that illustrate the flow dynamics around the tandem fish models. It might highlight how the wake of the leading fish influences the hydrodynamic environment experienced by the trailing fish, particularly focusing on the longitudinal velocity components.

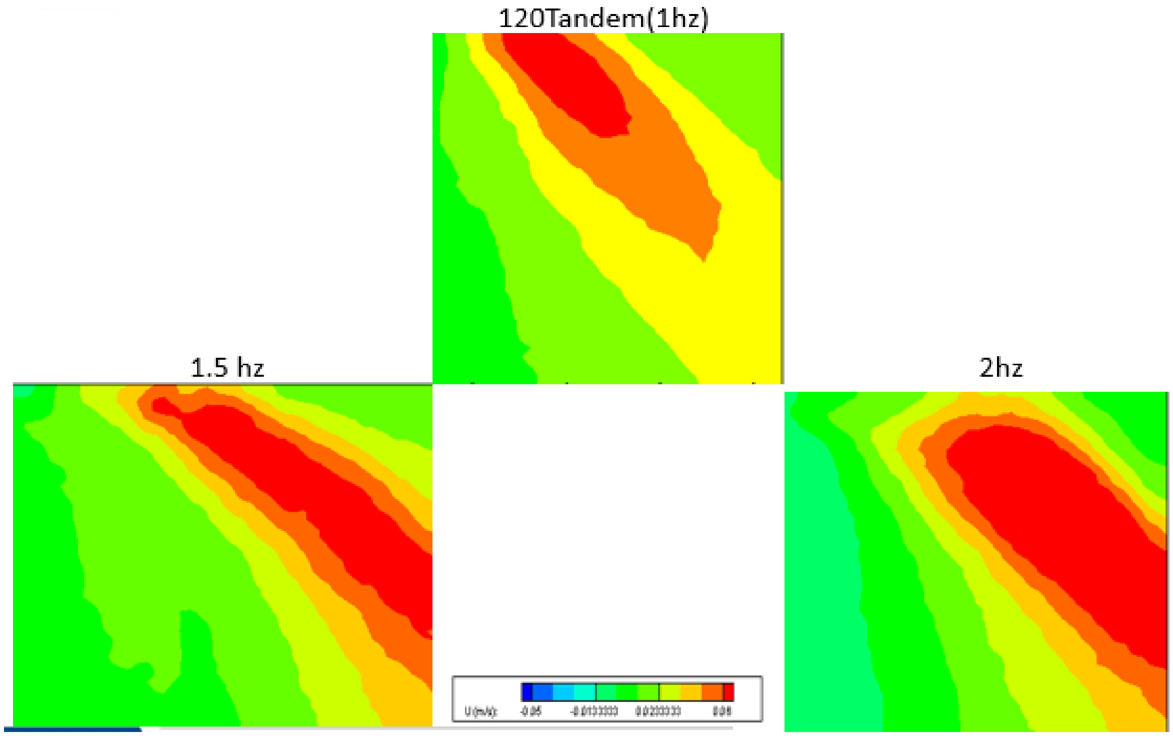


Figure 27 120 tandem Ux

Similar to Figure 26, this figure presents the Ux velocity in a tandem arrangement, but with a larger separation of 120 mm between the fish models. This figure also visualizes the longitudinal velocity patterns, but the increased distance between the fish models might result in different wake interactions and flow characteristics compared to the 60 mm arrangement. The figure could reveal how varying distances in tandem formations affect the propulsion efficiency and hydrodynamic advantages of following fish. Both figures are essential in understanding the complex fluid dynamics in fish swimming, especially focusing on how fish in a school or group can optimize their propulsion efficiency by adjusting their positions relative to each other. These insights are valuable for biomimetic applications, where understanding natural swimming strategies can inform the design of efficient aquatic vehicles or robotic swimmers.

4.4 Wake Width Analysis

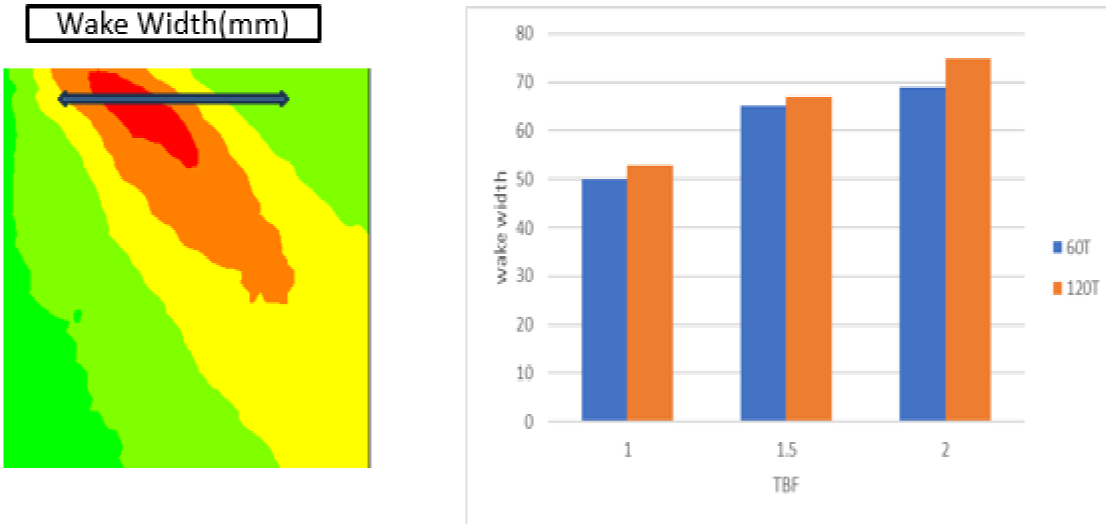


Figure 28 Wake width Tandem

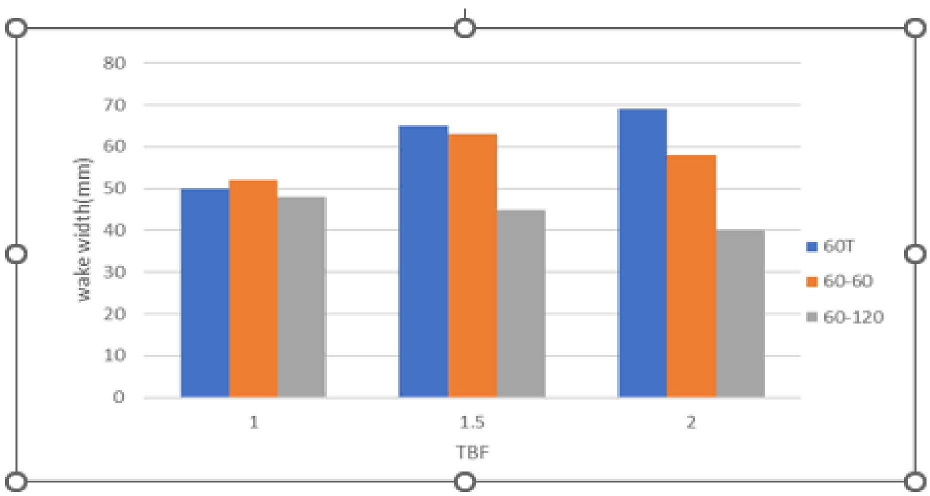


Figure 29 Wake width 60 staggered

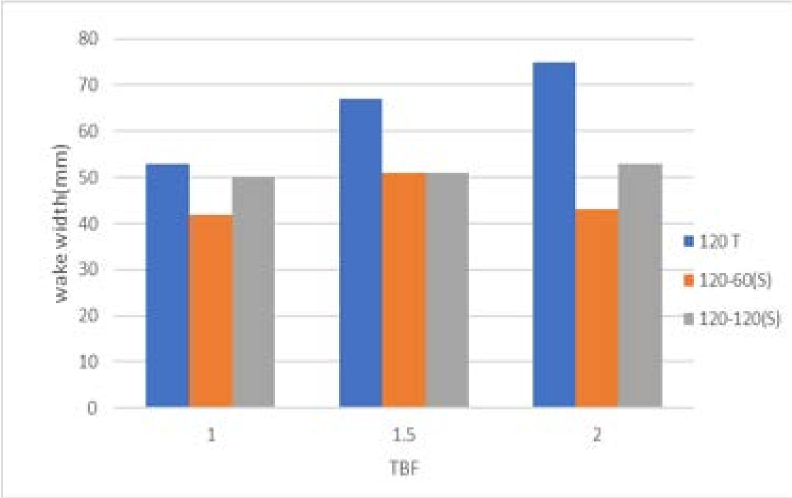


Figure 30 Wake width 120 Staggered

These three figures 28-30 present data related to the wake width generated by fish models under different arrangements. This could include measurements of wake width in various configurations such as tandem and staggered formations. The wake width is a crucial parameter in understanding the hydrodynamic interactions between swimming fish or bio-inspired robotic swimmers. Different arrangements would result in varying wake widths, which in turn influence the propulsion efficiency and energy consumption of following fish or vehicles.

4.5 TURBULENT KINETIC ENERGY W.R.F TO 6200 RE

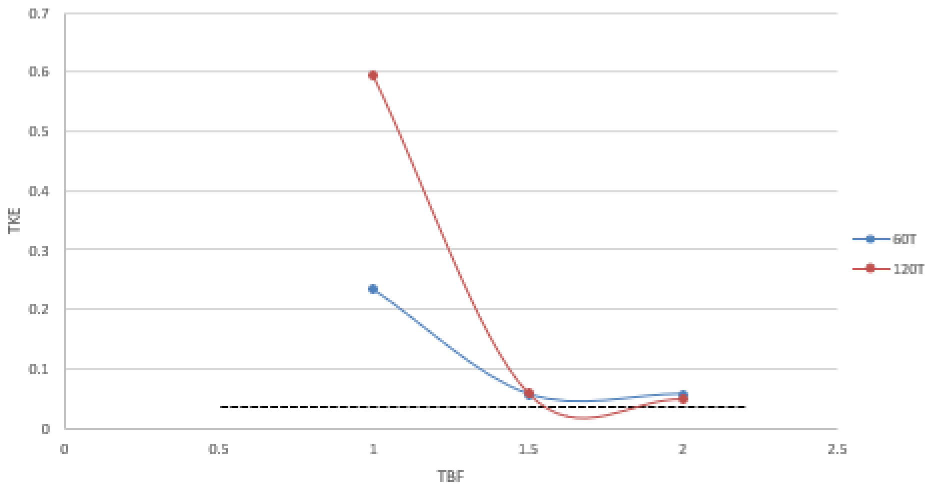


Figure 31 TKE Tandem

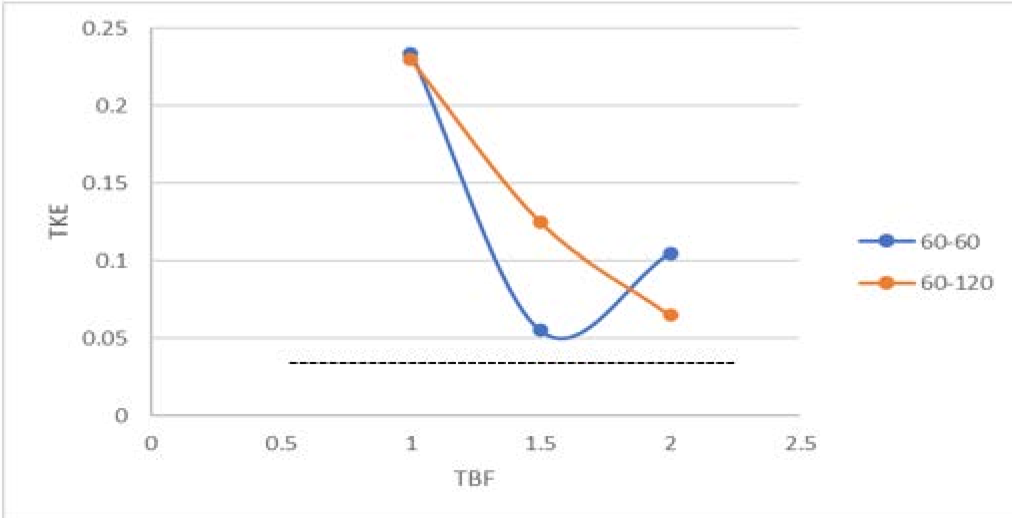


Figure 32 TKE 60 Staggered

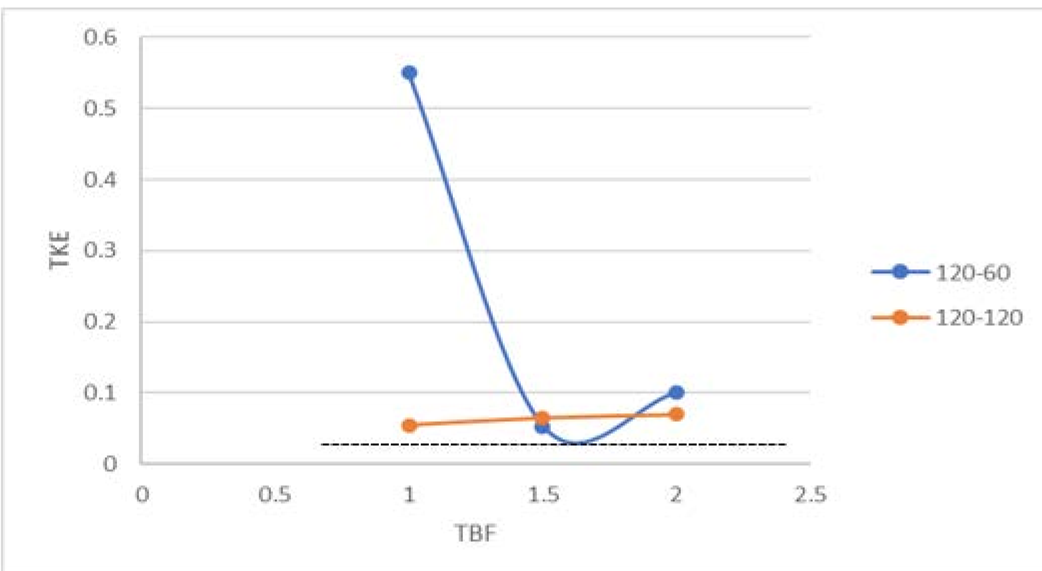


Figure 33 TKE 120 Staggered

It contain data on the Turbulent Kinetic Energy (TKE) under different experimental conditions. TKE is a key metric in fluid dynamics, indicative of the energy in turbulent flow. The tables show how TKE varies with different fish arrangements (tandem and staggered) and possibly at different tail beat frequencies. Higher TKE can indicate more turbulent flows, which could affect swimming efficiency. The comparison across different configurations would provide insights into the most energy-efficient swimming strategies or the best configurations for minimizing energy expenditure in aquatic locomotion.

CHAPTER 5 CONCLUSION AND RECOMENDTION

5.1 Conclusion

• In this experimental study, we found out that the higher the tail beat frequency the smaller vortex size (at tail) and hence propagation is seen in both x and y axis.

• For tandem fish cases, the best hydrodynamic advantages are seen at lower tail beat frequency of 1 hz at Reynolds number 6200.

• Low hydrodynamic advantages are seen for both vortex wake width and high vortex velocity is seen at 2Hz tail beat frequency.

• At staggered approach fish's formation at 60 mm apart causes coupling of vortex in damping region causing higher vortices intensity.

• Distance larger than 120mm (1fish length) in staggered fish arrangement case would result in lower hydrodynamic efficiency (negligible).

• For Reynolds number at 6200, the best hydrodynamic advantages are seen at 1hz tail beat frequency for tandem (120mm)-fish case.

• At 6200 Reynold number higher turbulent kinetic energy (TKE)is seen at tandem cases as compared to staggered cases (120 tandem).

• Whereas in staggered section a spike of TKE is seen at 2hz tail frequency due to vortices coupling and higher velocities.

• At 120 mm apart staggered approach TKE almost remain affected as both fishes are at least position to influence.

• Wake regions have influence at 1 fish length, after that vortex are dissipated from fish thus best hydrodynamic characteristics were acquired at tandem approach of 1 fish length.

• 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, taking advantage of vortex phase matching (VPM).

• The overall finding of this study is that the shape of the fish is a critical aspect along with the tail beat frequency, flow velocity and rotation of caudal fin.

• The kinematics of hydrodynamic turbulent flows was studied in detail in flow patterns to date for the purposes of modifying existing devices and to allow for the passage of all fishes.

5.2 Future recommendations

In future studies, flapping mechanisms would be installed inside silicone molded fish.

• Moreover, the movement of fins would also be accounted for in research.

• 3D PIV, Stereo PIV, DPIV or LDV would be used to have better resolution and results.

• Frictionless towing carriages should be used to find thrust, drag etc.

• Detailed numerical simulation by incorporating different Reynolds number & tail beat frequencies.

• A hotwire anemometry test should be performed to measure hydrodynamic forces & Shedding Frequency.

REFRENCES

[1] Sakakibara, J., Nakagawa, M. & Yoshida, M. Stereo-PIV study of flow around a maneuvering fish. Exp Fluids 36, 282–293 (2004). https://doi.org/10.1007/s00348-003-0720-z.

[2] Zhu, Joseph & White, Cygel & Wainwright, Dylan & Di Santo, Valentina & Lauder, George & Bart-Smith, Hilary. (2019). Tuna robotics: A high-frequency experimental platform exploring the performance space of swimming fishes. Science Robotics. 4. eaax4615. 10.1126/scirobotics. aax4615.

[3] https://wevolver.com/wevolver.staff/bio-inspired.underwater.robot.

[4] https://www.ed.ac.uk/news/2021/squid-inspired-robot-is-masterstroke-of-design.

[5] Katzschmann, Robert & DelPreto, Joseph & MacCurdy, Robert & Rus, Daniela. (2018). Exploration of underwater life with an acoustically controlled soft robotic fish. Science Robotics. 3. eaar3449. 10.1126/scirobotics. aar3449.

[6] Chu, Won-Shik & Lee, Kyung-Tae & Song, Sung-Hyuk & Han, Min-Woo & Lee, Jang-Yeob & Kim, Hyung-Soo & Kim, Min-Soo & Park, Yong Jai & Cho, Kyu-Jin & Ahn, Sung-Hoon. (2012). Review of Biomimetic Underwater Robots Using Smart Actuators (vol 13, pg. 1281,38 2012). International Journal of Precision Engineering and Manufacturing. 13. 10.1007/s12541-012-0171-7.

[7] David Scaradozzi, Giacomo Palmieri, Daniele Costa, Antonio Pinelli, BCF swimming locomotion for autonomous underwater robots: a review and a novel solution to improve. control and efficiency, Ocean Engineering, Volume 130, 2017, Pages 437-453, ISSN 0029-8018, https://doi.org/10.1016/j.oceaneng.2016.11.055.

[8] K. Feng, H.X. Liu, Y.Y. Su, Y.M. Su, Numerical study on the hydrodynamics of C-turn maneuvering of a tuna-like fish body under self- propulsion, Journal of Fluids and Structures, Volume 94, 2020, 102954, ISSN 0889-9746, https://doi.org/10.1016/j.jfluidstructs.2020.102954.

[9] Gen Li, Dmitry Kolomenskiy, Hao Liu, Benjamin Thiria, Ramiro Godoy-Diana bioRxiv 596023; Doi: https://doi.org/10.1101/596023.

[10] https://www.mclaren.com/racing/f1-playbook/slipstream/

[11] M. Sfakiotakis, D. M. Lane and J. B. C. Davies, "Review of fish swimming modes for aquatic locomotion," in IEEE Journal of Oceanic Engineering, vol. 24, no. 2, pp. 237-252,

April 1999, Doi: 10.1109/48.757275.
[12] Manela A, Howe MS. The forced motion of a flag. J Fluid Mech 2009; 635:439-54.
[13] https://ecomodder.com/forum/showthread.php/bluefin-tuna-template-24759.html
[14] 14. Newlands, Nathaniel & Porcelli, Tracy. (2008). Measurement of the size, shape and structure of Atlantic bluefin tuna schools in the open ocean. Fisheries Research. 91. 42-55. 10.1016/j.fishres.2007.11.019.
[15] https://doi.org/10.1007/978-981-15-4756-0. springer journal.
[16] Diego Moreira, Nuno Mathias, Tiago Morais, Dual flapping foil system for propulsion and harnessing wave energy: A 2D parametric study for unaligned foil configurations, Ocean Engineering, Volume 215, 2020, 107875, ISSN 0029-8018, https://doi.org/10.1016/j.oceaneng.2020.107875.
[17] Fish, Frank. (2010). Swimming Strategies for Energy Economy. Fish Locomotion: An Eco-ethological Perspective. 10.1201/b10190-5.
[18] Arslan, Erdem & Akça, Kadir. (2019). A Design Methodology for Cuttlefish Shaped Amphibious Robot. European Journal of Science and Technology. 214-224. 10.31590/ejosat.637838.39
[19] J. Han, Z. Hui, F. Tian, G. Chen, Review on bio-inspired flight systems and bionic aerodynamics, Chinese Journal of Aeronautics (2020), Doi: https://doi.org/10.1016/j.cja.2020.03.036.
[20] Xia Wu, Xiantao Zhang, Xinliang Tian, Xin Li, Wenyue Lu, A review on fluid dynamics of flapping foils, Ocean Engineering, Volume 195, 2020, 106712, ISSN 0029-8018, https://doi.org/10.1016/j.oceaneng.2019.106712.
[21] Hydrodynamics of median-fin interactions in fish-like locomotion: Effects of fin shape and movement. Phys. Fluids 32, 011902 (2020); https://doi.org/10.1063/1.5129274.
[22] Dagenais, P., & Aegerter, C. (2020). How shape and flapping rate affect the distribution of fluid forces on flexible hydrofoils. Journal of Fluid Mechanics, 901, A1. doi:10.1017/jfm.2020.489.
[23] Wang J, Wainwright DK, Lindengren RE, Lauder GV, Dong H. 2020 Tuna locomotion: a computational hydrodynamic analysis of finlet function. J. R. Soc. Interface 17: 20190590. http://dx.doi.org/10.1098/rsif.2019.0590.
[24] arXiv:2009.12715 [physics.flu-dyn].

[25]https://youmatter.world/en/definition/definitions-what-is-biomimicry-definitionexamples/#google_vignette.

[26] Willis, Jay. (2013). Wake sorting, selective predation and biogenic mixing: Potential reasons for high turbulence in fish schools. PeerJ. 1. e96. 10.7717/peerj.96.

[27] Chuin, lai hoong. (2019). Flow Field Measurement of Wake Generated by Gourami Fish Tail. Springer Singapore. Proceedings of International Conference of Aerospace and Mechanical Engineering 2019. 10.1007/978-981-15-4756-0_18.