A COMPUTATIONAL FLUID DYNAMICS ANALYSIS OF OSCILLATING BLUEFIN TUNA FOIL PROPULSION

By

INSHA AHMED TARAY

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

March 2021

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DEDICATION

In the name of Allah, Most Gracious, Most Merciful
Praise be to Allah, the Cherisher and Sustainer of the worlds
Most Gracious, Most Merciful
Master of the Day of Judgment
Thee do we worship, and Thine aid we seek
Show us the straight way
The way of those on whom Thou hast bestowed Thy Grace
those whose (portion) is not wrath
and who go not astray

I am dedicating this thesis to my dearest parents for their unconditional love and support and for planting a love for the pursuit of knowledge; to my siblings for their faith in me and because they always understood; to my husband and friend, for his patience, and wholehearted substantial support;

And

My bubbala, Hamzah Omar.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

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March 2021

Chairman : Associate Professor Azmin Shakrine Bin Mohd Rafie, PhD
Faculty : Engineering

There is an on-going interest in analysing the flow characteristics of swimming fish-like bodies. Bio-inspired aquatic life has inspired some efficient and optimum designs for mankind. The design of both aerial and underwater vehicles has advanced over last few decades and new propulsion methods are being considered to further improve the existing designs. The study of fish locomotion has resulted in some very efficient motions and it has become an interest among scientists to formulate these motions. One such motion is thunniform locomotion (which means to swim like tuna) in which the undulations are confined to the tail (peduncle and caudal-fin) only. Bluefin tuna employs thunniform locomotion and has been associated with a high propulsive efficiency but with less experimental and computational base. Computational fluid dynamic analysis was done using Ansys Fluent for typical range of Strouhal numbers (0.183, 0.281 and 0.413) on a tuna-like body investigating the hydrodynamic forces and flow patterns of the tuna-swimming wake; the time-averaged resultant thrust for above three cases were found to be 0.728 N, 0.803 N and 0.9538. It is seen that higher the value of Strouhal number, more are the shed vortices in the wake. The thunniform motion designed in this study was compared with the existing 3D experimental studies through physical entity of thrust. The vortex shedding was recorded and visualized using curl of velocity and helicity method for vortex core region. The scope of this research has consequences in the design of aircrafts, airships, UAV's, UUV's, submarine-launched UAVs, winged vehicles to the jet-propelled take-off and submarines.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

SEBUAH ANALISIS PENGKOMPUTERAN DINAMIK BENDALIR KE ATAS CORAK AYUNAN DAYA TUJAHAN BERBENTUK TUNA SIRIP BIRU

Oleh

INSHA AHMED TARAY

Mac 2021

Pengerusi : **Profesor Madya Azmin Shakrine Bin Mohd Rafie, PhD**
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Terdapat kajian yang sedang dijalankan untuk menganalisa ciri-ciri aliran renangan pada bentuk badan mirip ikan. Terjemahan ilmu hasil inspirasi daripada hidupan akuatik ini telah mengilhamkan suatu reka bentuk yang optimum dan berkesan untuk manusia sejagat. Reka bentuk kenderaan udara dan bawah air telah berkembang sejak beberapa dekad yang lalu dan kaedah tujahan baru sedang dipertimbangkan dalam usaha menambah baik lagi reka bentuk yang sedia ada. Kajian mengenai pergerakan ikan telah menunjukkan beberapa siri gerakan yang sangat cekap dan menjadi faktor kecenderungan para saintis untuk dirumskan. Salah satu pergerakan tersebut adalah Pergerakan Bentuk Mirip Tuna - Thunniform (yang bermaksud berenang seperti ikan tuna) di mana cara pergerakannya terbatas hanya pada ekor (peduncle dan sirip ekor) sahaja. Tuna bersirip biru memiliki pergerakan Thunniform dan sering dikaitkan dengan kecekapan tujahan yang tinggi tetapi kurangnya asas eksperimen dan pengiraan. Analisa CFD (Computational Fluid Dynamics) telah dilakukan menggunakan Ansys Fluent untuk julat nombor Strouhal (0.183, 0.281 dan 0.413) pada bentuk mirip tuna untuk menyelidiki daya hidrodinamik dan corak aliran gelombang hasil renangan ikan tuna; purata masa daya tujahan untuk tiga kes di atas adalah 0.728 N, 0.803 N dan 0.9538 N. Ia jelas menunjukkan semakin tinggi nilai nombor Strouhal, semakin banyak pusaran yang dihasilkan. Pergerakan Bentuk Mirip Tuna (Thunniform) yang dijalankan dalam kajian ini telah dibandingkan dengan kajian 3D yang sedia ada melalui entiti fizikal daya tujahan. Limpahan pusaran telah direkodkan dan divisualisasikan menggunakan kaedah lengkungan halaju dan lingkaran pada kawasan teras pusaran. Hasil penyelidikan ini membawa kepada permulaan dalam reka bentuk pesawat, kapal udara, UAV, UUV, UAV hasil lancaran kapal selam, kenderaan bersayap hinggalah kepada kapal sayap berputar serta kapal selam.

ACKNOWLEDGEMENTS

All praise and thanks to Allah the exalted, the Lord of the universe. May the choicest blessings and peace of Allah be upon the last Messenger Prophet Muhammad pbuh, his family, companions and all those who follow his footsteps till the end of this universe.

I would like to express my deepest gratitude to my supervisor, Associate Professor Dr. Azmin Shakrine, for his steadfast knowledgeable guidance, sage advice, great encouragement and generous support to conduct this research. Thank you, sir, for being very kind to me in the unkindest times of life.

Furthermore, I am very grateful to Associate Professor Dr. Mohammad Zuber for giving me an opportunity to work on a bio-inspired topic. Thank you for encouragement and imparted guidance to me all the way from Manipal Institute of Technology.

Lastly, I want to thank my friend, Dr. Abdur Razzak of National University of Singapore for his advice, and for providing me consultation from time to time.

This thesis was submitted to the Senate of the Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

BCF	Body and caudal fin
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
GAU	Glide and Upward
GCI	Grid Convergence Index
MIT	Massachusetts Institute of Technology
MPF	Median and paired fin
NACA	National Advisory Committee for Aeronautics
PBT	Pacific Bluefin Tuna
PISO	Pressure Implicit with Splitting of Operators
RNG	Re-Normalisation Group
SIMPLE	Semi Implicit Method for Pressure Linked Equations
UIUC	University of Illinois at Urbana-Champaign
UDF	User Defined Function

LIST OF SYMBOLS

y	Absolute distance
ρ	Density
μ_t	Dynamic eddy viscosity
A	Flapping amplitude
f	Frequency
ω	Frequency of Oscillation
u_τ	Friction velocity
L	Length
l	Length
ϕ	Transport property
l	Length
ϕ	Rate of increase
ϵ	Rate of dissipation of turbulent kinetic energy
S_m	Source term
U	Speed
p	Static pressure
ϕ	Transport property
k	Turbulent Kinetic Energy
ν	Viscosity
y^+	Wall distance
τ_w	Wall shear
λ	Wavelength
k_w	Wavenumber

CHAPTER 1

INTRODUCTION

1.1 Research Motivation

Biomimicry (coined by: Janine Benyus; Greek Bios (life) and mimesis (imitation)) is the conscious emulation of life's form, a more recent concept, even though Humans have been gaining inspiration from nature for thousands of years. As scientific explorers, one needs to attune human behavior with the wider world to solve global challenges. Across the globe, there has been a steady increase in biomimetic innovations helping to design and deploy products in more sustainable ways. There are ample examples of such innovations: the Shinkansen Bullet Train of the West Japan Railway inspired by the Kingfisher's beak, the Eastgate Building in Zimbabwe taking inspiration from termites' self-cooling mounds, and British Telecom using a biological model based on ant behavior to overhaul its phone network. The Spiroid Wing Tip of gulfstream II aircraft developed at Boeing utilized the reduced induced drag of wing-tip vortices with devices inspired by winglets of soaring eagles, and the Bannasch's tipless round blades of propellor are such aeronautical examples. Such scientific innovations inspired by nature are vitally important part of our transformation towards a more cost effective and a sustainable future. Therefore, the efficiency of the current engineering devices could be increased and solved through mimicking both flying and swimming animals.

In the last few decades, unconventional fish-like bodies are being researched and investigated with the possibility of being able to capture the unbridled energy contained within the oceans. It is known that 71% surface on the Earth is just water; naturally, making it a centre of scientific attention. The underwater environment is far from calm-quiescent realm than it is often imagined to be. The turbulence, energetic currents, and rapidly-progressing flow structures make ocean a complex world and intriguing topic of study. Through research, it is understood that aquatic animals achieve a greater propulsive efficiency and manoeuvrability despite the turbulent nature of the deep waters which is dominated by waves and vortex structures (Barrett et al., 1999). Bio-inspired aquatic life has inspired some efficient and optimum designs for mankind. The hump-back whales provided efficient turbines; Dolphins have led to a better communication and signalization as well as their design has inspired the shape of modern boat hulls and submarines such as the US Albacore launched in 1953. Many autonomous underwater vehicles have been designed from the fish fins (Bozkurttas et al., 2008). Some of the technical problems related to fluid dynamics of aerial and submerged devices can efficiently be solved by mimicking swimming animals and insects (Muratoglu & Muratoglu, 2017). Among other aquatic animals, tadpoles have also been studied for hydrodynamic efficiency (Liu et al., 1996) which highlighted the use of its hindlegs with a hybrid form of swimming as compared to the fish.

In aircraft design, it's essential to address the fuel efficiency goal by reducing aircraft weights, improving propulsive efficiency, improving the aerodynamics of the aircraft wings. With the need for green energy as the world descends into the environmental chaos caused by the greenhouse gas emissions, it has become essential to design the futuristic airplanes that could possibly decrease drag which would in turn increase fuel efficiency, reducing both costs and emissions. Such improvements can be sought out through the bio-inspiration including the study of the design and function of the fast-moving fish which will unlock the aspects that remain unseen through traditional airplane design techniques. The body fins of the fish have a semblance of design to the airplanes when it comes to: rudders, stabilizers, brakes, spoilers depending on the need.

By being able to simplify the complex motions of fish locomotion into simple mechanical systems, it will allow us to design more efficient propulsion devices including submarines and airships. Marine animals such as fish are neutrally buoyant in water and their swimming techniques created to self-propel them forward makes them ideal for the study of these vehicles. By using the principle of fluid dynamic similarity, it is possible to translate movement from water into the air. Therefore, being able to create such a mechanical system would only benefit in increased travel durations, lighter payloads, and more sustainable transportation. Hence, proving the importance of the study of different fish.

A limited number of computational studies have been published on Tuna's, especially the Bluefin Tuna that are considered as the largest of the Tuna species weighing about 400 kg approximately with body length of 2-4m, easily. Figure 1.1 displays the Atlantic Bluefin Tuna captured in action. Bluefin Tuna, with the help of their torpedo shaped and streamlined body, are known as one of the fastest and largest sea animals, reaching a speed of around 100 km/h. They have been called the superfish by none other than David Attenborough. Their torpedo shaped body is the most hydrodynamic shape possible with the widest part occurring at 2/5th of the distance from head to tail, and the tail is tall, swift, and swept back forming into a lunate tail (Graham & Dickson, 2004). The bluefin tuna harness the thunniform mode of locomotion. The term thunniform, literally means to swim like tuna. In thunniform locomotion, the thrust is generated exclusively by the posterior part of their body characterized by their tail, known as the caudal fin. It is one of the fastest ways of swimming.

Figure 1.1 : Atlantic bluefin tuna near the bottom (Source: Brian Kerry, 2014)

Besides being the fastest thunniform species, they are considered warm blooded unlike any other fish which dives in pelagic zones (maximum depth = 11km), which has proved to help them swim faster (Lindsey, 1978). The Bluefin tuna have an amazing swimming efficiency of the range of nearly 80% (Zhang et al., 2011).

Thus, the extent of consequences of this research starts in the design of aircrafts, airships, UAV's, UUV's, submarine-launched UAVs, winged vehicles to the jet-propelled take-off and submarines. The importance of these improved underwater vehicles remains essential in the fields of oceanographic observation, archaeological explorations underwater, leakages in pipelines, environmental reasons, scientific studies. It is important to engage this study area for research and establish technologies that protect and exploit underwater resources more efficiently.

In this study, a body shape representing a form of tuna is re-created using CAD software, Catia V5R20. This shape is based on RoboTuna of Barrett et al. (1999) developed by MIT in 1999 and is the closest shape possible to a real-life Bluefin Tuna. As wave-like motion of the thunniform locomotion is mimicked by creating a special user defined function which is later compiled in Ansys Fluent (Stevens & Neill, 1978). A UDF (user defined function) is created which translates the theoretical thunniform locomotion into a proper dynamic motion inside the CFD solver (Ansys Fluent). The data from the simulations is then used to validate the UDF with existing values of thrust. This study analyses the results of three cases of computational fluid dynamic simulations with different kinematic performance parameters based on the experimental real-life fish. Included are descriptions of the wake, thrust, drag and lift. The effects of Strouhal number on the hydrodynamic forces quantified as thrust and lift are included.

By being able to solve these mechanical properties, we come closer to understanding the design and functionality of the tuna. This research acts as a binding study that shows the important differences between 2D and 3D fish swimming. The basic principles are carried over from 2D and 3D, but 3D contains much more complex wake and some mechanisms which are not present in 2D. Since 3D simulations require significantly high computational power and time to conduct, this research has been limited to 2D investigation.

1.2 Problem Statement

The design of both aerial and underwater vehicles has advanced over last few decades and new propulsion methods are being considered to further improve the existing designs. The disadvantages of such vehicles lie in low efficiency, poor manoeuvring performance, significant noise among others; which limits their applications in a real dynamic and complex environment. Many bio-inspired concepts are being translated into a reality to provide an answer to the disadvantages of these vehicles.

It all started with gray's paradox (Gray, 1936) who estimated the power requirements of a swimming dolphin. Over time there have been many improvements in this field of study of fish locomotion but still a lot of mechanical properties of the flow field around swimming bodies remain undetermined which prove to be valid impediments in implementing design of bio-inspired animals to a reality.

Among different modes of swimming, the thunniform swimming mode was chosen for this study. The evolution has led the most superior species to adapt to the most superlative design of 'thunniform' because of its unique propulsor (the caudal fin) which confines the undulation to its tail. Bluefin tuna employs thunniform locomotion and has been associated with a high propulsive efficiency but with less experimental and computational base. Thus, bluefin tuna is chosen for this study because of its advantages in both design and propulsive efficiency.

Through this research, we try to understand the proportion theory of fish by taking inspiration from the bluefin tuna and understand it's working design functionality by quantifying Strouhal number and the wake vortex street. The importance of dimensionless numbers in biomechanics implies consistency of dynamic similarity between systems, regardless of the difference in the medium and a scale. Strouhal number which is a dimensionless parameter describes the kinematics of wings or tails in flying or swimming animals. It is given by a ratio of stroke frequency with amplitude by a forward speed. It, also, governs the vortex growth and shedding regimes for airfoil and hydrofoils undergoing any pitching, heaving or in this case: oscillatory motion. (Rohr et al., 1998; Wang, 2000). The Strouhal number affects the aerodynamic and hydrodynamic force coefficients as well as propulsive efficiency, because it defines the maximum aero/hydro-dynamic angle of attack and the timescales associated with the growth as well as the shedding of vortices, which are the source of aero/hydro-dynamic force production (Wang, 2000; Huang, 2001).

This study is an attempt to more fully understand the hydrodynamics of a swimming bluefin tuna and will compare results of simulation using a 2D version of the tuna body for the flow structures to the previous study carried out by Zhu et al. (2002).

In this study, the parameters of wavelength, oscillation frequency, and amplitude coefficients were varied with constant swimming velocity to investigate the thrust production which has a dependency on the Strouhal number similar to the thunniform locomotion upon which this model is based on, and is in consensus with previous studies (Eloy, 2021; Taylor et al., 2003; Triantafyllou et al., 1993). Therefore, it can be said that this study emphasizes the importance and correlation between the Strouhal number and hydrodynamic coefficients.

1.3 Research Objectives

The research objectives can be broken into three sub-research objectives which are described in subsequent statements:

1. To conduct CFD simulation analysis on the constructed oscillating bluefin tuna foil propulsion model.
2. To establish the effects of Strouhal number on the hydrodynamic forces and flow patterns of the induced swimming wake.

1.4 Thesis Scope and Limitation

The initial purpose of this study was to capture fluid flow around three-dimensional Tuna, but due limitations in computational resources, a 2D study was done. Hence, following simplifying assumptions have been made, in order to reduce the computational cost:

A two-dimensional dynamic study was performed using the planform view from three-dimensional CAD file of the Tuna. As a general rule, the two-dimensional simulations are generally very well translatable into the three-dimensional simulations. This is supported by the study done by Maertens et al. (2017). This assumption helps reduce the computational time and cost. The main findings of this paper can be applied to the three-dimensional simulations as well.

The major goal of this study is to imitate the oscillatory movement of the caudal fin. While finlets, and other retractable fins have some role too, but this study focuses on the tail which is the primary source of propulsion in Tuna.

This study does not incorporate complex motions like bending, pitching, and flexing of the tail, as well as the fin retractions are not included; these are, however, utilized by the real fish.

In order to match the parameters from Zhu et al. (2002) which is based on the experimental studies, a Re = 7.43×10^6 is used. The flow is turbulent, and a Realizable k-**ε** model is used. This model is chosen because of its impeccable ability to capture flows with strong adverse pressure gradients or separation. It is a defacto model for capturing vortex flows in highly turbulent environment.

1.5 Thesis Organization

This thesis is organized into 5 chapters:

Chapter 1 is a brief introduction to the thesis project, which reveals the importance to understand the computational fluid mechanics of Bluefin Tuna and lists the goals of this thesis.

Chapter 2 reviews the literature on Bluefin Tuna in four parts: Thunniform locomotion, Undulatory motion and propulsion, Energy efficiency and energy extraction, and all the recent computational studies.

Chapter 3 focuses on methodology, creating the model in CAD software, solver theory, UDF creation, and basics of dynamic meshing. Two airfoils have been validated: Clark-Y and NACA 0012 in Ansys Fluent; the data from CFD software is compared with experimental values. An error estimate is done.

Chapter 4 presents the hydrodynamic analysis of the Tuna in CFD in the form on velocity contours, vortex contours, plots of thrust, lift, velocity profiles. This is the essential part of the thesis.

Chapter 5 contains the conclusions, thesis contributions, limitations, and some outlook on possible further research activities in the area of this thesis.

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