Towing Tank Trials of Hydrokinetic Turbine Scale Model to Support Marine Energy System Verification

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Towing Tank Trials of Hydrokinetic Turbine Scale Model to Support Marine Energy System Verification

A Dissertation

Submitted to the Graduate Faculty of the
University of New Orleans
In partial fulfillment of the
Requirements of the degree of

Doctor of Philosophy
in
Engineering and Applied Science

By
Shahab Rouhi
May, 2024
Dedication

To my dearest wife Setare and our precious little daughter Seren,

In the journey of academic pursuit, your unwavering love, boundless support, and the joyous laughter of our little one have been my constant companions. This dissertation stands not only as a testament to scholarly achievement but also as a tribute to the strength, encouragement, and warmth you have infused into every step of this challenging yet rewarding expedition.

Setare, your patience during late nights of research, understanding through moments of academic intensity, and the comfort you provided have been my pillars of strength.

To our dear Seren, your innocent smiles and playful presence filled each day with inspiration and purpose.

May this work be a reflection of the love that surrounds me daily. With immense gratitude and love, I dedicate this dissertation to both of you, the heart and soul of my life.

Forever Yours,

Shahab Rouhi
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Together, your combined efforts have played a pivotal role in shaping the trajectory of this project. I am truly grateful for the opportunities to learn from your wisdom, work alongside you, and benefit from your unwavering support.

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With sincere appreciation,

Shahab Rouhi
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Abstract
In response to the escalating demand for sustainable energy solutions and the critical reevaluation of conventional fossil fuels due to environmental concerns, this dissertation embarks on a comprehensive exploration of hydrokinetic energy as a promising alternative. The study delves into the underexplored domain of hydrokinetic energy, leveraging innovative methodologies for effective utilization and harnessing, particularly through the development and investigation of hydrokinetic turbines.

In the realm of hydrokinetic energy conversion, our research has exclusively concentrated on horizontal-axis turbines, distinct from other turbine configurations. Noteworthy is the adaptation of a conventional horizontal-axis wind turbine for water currents, revealing enhanced performance through experimental and computational methodologies, emphasizing the unique properties of water and insights gained from computational fluid dynamics (CFD) analysis.

Parallel to the developmental trajectory of wind turbines, the dissertation emphasizes the need for empirical validation through systematic experimentation to understand and optimize the behavior of hydrokinetic turbines. A novel testing approach, utilizing towing tanks commonly employed in maritime engineering, is introduced. This approach, focused on the conversion of ocean currents' kinetic energy, parallels the testing methodologies used for wind turbines, highlighting the commonality with horizontal-axis turbines. Specialized numerical methods, validated through a simulation tool based on Blade Element Momentum (BEM) theory, enhance confidence in the applicability of these methods for marine current turbine development.

The groundbreaking methodology for dynamometer testing of hydrokinetic turbines is a central focus of the research. Utilizing towing tanks as a testing platform, this approach involves a minimized hydrokinetic turbine model enclosed within a 3D-printed watertight nacelle. Integrated sensors capture crucial parameters, enabling comprehensive data collection for energy consumption, torque, and power generation. This methodology presents a promising avenue for advancing the development of hydrokinetic turbines, aiming for standardized and verifiable procedures for testing and experimentation.

The study extends its reach to the potential market opportunities derived from harnessing hydrokinetic energy, drawing parallels between hydrokinetic turbines and wind turbines. The dissertation outlines a systematic testing and development approach inspired by well-established methods in the wind energy sector, aligning with the guidelines of the International Towing Tank Conference (ITTC). The proposed methodology, organized into several chapters, covers aspects such as adaptation of towing tanks, selection of scale models, instrumentation and sensors, dry dynamometer characterization, nacelle design, testing procedures, and redesign with magnetic coupling.

In essence, this dissertation seeks to revolutionize underwater turbine testing by integrating principles from naval architecture and adapting them to the unique challenges of hydrokinetic energy. The proposed methodology ensures robustness, repeatability, and valuable insights into the hydrodynamic performance of hydrokinetic turbines, contributing significantly to the advancement of ocean current energy conversion technologies.

Keywords: Hydrokinetic Energy Conversion, Ocean Current Turbine (OCT), Small-Scale Ocean Current Turbine, Blade Element Momentum (BEM) Simulations, Mathematical Modeling, Dynamometer Testing, Sensor-Equipped 3D-Printed Turbine, Towing Tank Tests, Magnetic Coupling, Leakage-Free Testing
1. Chapter 1: Introduction

In the contemporary era, the escalating demand for sustainable energy solutions has catalyzed a critical reevaluation of conventional fossil fuels. This imperative shift towards sustainable alternatives is underscored by the adverse environmental impacts associated with ordinary petroleum derivatives [1-5]. Within this landscape, hydrokinetic energy has emerged as a particularly promising and economically viable asset, drawing its potential from the kinetic movement of water bodies such as streams and oceans [6-10]. However, despite its substantial potential, the practical implementation of hydrokinetic energy remains relatively underexplored within the energy domain, necessitating innovative methodologies for effective utilization and harnessing [11-14].

The exploration of alternative energy sources, driven by the limitations of conventional reservoirs, has led to the development of hydrokinetic turbines. These turbines possess the unique capability of utilizing the distinctive properties of water to generate power, marking a significant advancement in the field of renewable energy technologies [15-20].

Turbine Configurations and Investigations:

The domain of hydrokinetic energy conversion has witnessed a plethora of investigations, encompassing various turbine configurations. Studies have delved into different aspects, examining the performance characteristics of horizontal-axis, vertical-axis, cross-flow, and oscillating hydrofoil designs [21-27]. Notably, the performance of a conventional Savonius wind turbine has been scrutinized to adapt for water currents through experimental and computational methodologies [28-31]. The results revealed enhanced performance compared to its wind counterpart due to water's properties and improved understanding through CFD analysis [32-34].

Among the myriad turbine types, horizontal-axis turbines have gained global prominence. These turbines, often secured to the seafloor, differ from their wind turbine counterparts and are reminiscent of airborne wind turbines [35-48].

Empirical Validation and Testing Methodologies:

Similar to the developmental trajectory of wind turbines, empirical validation through systematic experimentation becomes essential for understanding and optimizing the behavior of hydrokinetic turbines [49-54]. In response to this need, a novel testing approach has emerged, utilizing towing tanks commonly employed in maritime engineering. This approach, focused on the conversion of ocean currents' kinetic energy, emphasizes the commonality with horizontal-axis turbines used in wind energy [55-60]. However, differences such as free surface effects and cavitation necessitate specialized numerical methods, leading to the development and validation of a simulation tool based on BEM theory [61]. Experimental verification demonstrated that BEM code offers comparable representations of turbine performance, instilling confidence in their applicability for marine current turbine development [62-67].

Investigations based on laboratory experiments and numerical models aim to determine the dynamics of turbulent wake cooperation and its consequences on the riverbed [68]. The results provide a comprehensive framework to assess the predictive capabilities, scope, and applicability of computational models defining turbines utilizing BEM for testing various turbine designs and siting strategies.
Dynamometer Testing Methodology:

This research introduces a groundbreaking methodology for dynamometer testing of hydrokinetic turbines, advancing the field towards standardized empirical assessment [69-78]. By utilizing towing tanks as a testing platform, this approach involves a minimized hydrokinetic turbine model enclosed within a 3D-printed watertight nacelle. Integrated sensors capture vital parameters such as rotational speed, force, voltage, current, humidity, and temperature. This experimental framework not only enables the quantification of energy consumption but also facilitates the extraction of essential hydrodynamic characteristics, including torque and power generation.

Hydrokinetic Turbines and Market Opportunities:

The potential of hydrokinetic energy as a plentiful and sustainable source of power is underscored by the similarity of hydrokinetic turbines to wind turbines. These turbines extract dynamic energy from water flow, converting it into rotational motion that drives an electric generator [79]. Horizontal-axis hydrokinetic turbines, anchored to the seafloor, have garnered significant interest due to their efficiency in converting energy from ocean currents. Given the relative newness of the field, innovative work on hydrokinetic turbines necessitates testing methodologies akin to those employed for wind turbines. To address this, a system has been developed for dynamometer testing, utilizing towing tanks—a common facility in maritime engineering for ship design and propulsion research. The proposed methodology aims to provide a standardized and verifiable procedure for testing and experimentation, contributing to the development of more efficient and dependable hydrokinetic turbines.

Several comprehensive studies have been conducted on hydrokinetic energy conversion utilizing various turbine types, including horizontal-axis, vertical-axis, cross-flow, and oscillating hydrofoils. These studies delve into the impact of factors such as stream rate, blade pitch angle, turbulence intensity, and blade configuration on turbine performance [80-85]. However, the field is still in its early stages, necessitating further comprehensive investigations to understand the nuanced performance and behavior of hydrokinetic turbines.

The proposed methodology for dynamometer testing utilizing a towing tank presents a promising avenue for advancing the development of hydrokinetic turbines. This work outlines a technique for testing small-scale hydrokinetic turbines, employing a towing tank and integrating essential sensors for comprehensive data collection. The ultimate goal is to propose a standardized technique for testing and verification that can be independently confirmed by third parties, contributing to the maturation of the hydrokinetic energy sector.

Performance Analysis and Experimental Investigations:

Global electricity demand is surging at a rate outpacing renewable energy production, leading to an increased reliance on fossil fuels. The economic potential and market opportunities derived from harnessing marine energy, particularly through moored ocean current turbines (OCT), present a promising avenue for sustainable energy generation. The performance analysis of turbines, both through simulation tools and experimental investigations using small-scale OCTs in laboratory settings, guides further developments for full-scale OCTs.
This dissertation delves into fundamental research aimed at understanding the performance of a permanent magnet direct current (PMDC) motor associated with a small-scale three-bladed horizontal axis ocean current turbine operating in a laboratory towing tank at the University of New Orleans. Various approaches have been considered to address the performance characteristics of PMDC motors, encompassing parameter identification, numerical modeling, control systems, and precise estimations of startup time and turbine speed.

**Research Objectives and Significance:**

The proposed methodology seeks to revolutionize the testing and development of underwater turbines, aligning its principles with well-established methods employed in the wind energy sector. Hydrokinetic turbines, akin to their wind counterparts, capture the kinetic energy of water currents, presenting a unique opportunity for sustainable energy generation.

**Central Objectives:**

The central objective of this methodology is to facilitate comprehensive testing and experimentation essential for the research and development of hydrokinetic turbines. Drawing inspiration from naval architecture practices, specifically the use of towing tanks, the methodology aims to emulate the well-established principles while adapting them to the distinctive requirements of underwater turbine testing.

**Alignment with ITTC Guidelines:**

The proposed methodology aligns closely with the guidelines advocated by the International Towing Tank Conference (ITTC). It delineates a structured approach encompassing key steps, ensuring a systematic and standardized procedure for hydrokinetic turbine testing.

**Structure of the Dissertation:**

This dissertation is organized into several chapters, each dedicated to specific aspects of the research.

1. **Adaptation of Towing Tank for Turbine Testing (Chapter 2):**
   The towing tank, traditionally utilized for ship model testing, undergoes necessary modifications to accommodate the testing of hydrokinetic turbine scale models. Specialized equipment and structures essential for turbine testing are installed during this phase.

2. **Selection of Scale Model (Chapter 2):**
   A meticulous selection process is employed to choose an appropriate scale model that accurately represents the full-scale hydrokinetic turbine system. Mathematical analysis guides the determination of the model's size, shape, and characteristics in alignment with the specific objectives of the testing.

3. **Instrumentation and Sensors (Chapter 2):**
   Various sensors and instruments are integrated into the test setup to capture a comprehensive array of data. These sensors, measuring parameters such as RPM, torque, voltage, and current,
along with additional humidity and temperature sensors, ensure safety and facilitate in-depth data collection.

4. Dry Dynamometer Characterization (Chapter 3):
A geared permanent-magnet direct-current (DC) motor is selected as the electro-machine for the dynamometer, ensuring compatibility with the testing setup. Rigorous calibration and testing of the chosen electro-machine set the foundation for accurate data collection during subsequent tests.

5. Nacelle Design and Construction (Chapter 4):
A watertight nacelle is meticulously designed and constructed to house the electro-machine and the hydrokinetic turbine model. Equipped with an array of sensors, this nacelle ensures the dry and secure enclosure of components during submersion in the towing tank.

6. Testing Procedure (Chapter 5):
The testing procedure involves configuring the electro-machine and turbine model to specified RPM values, mimicking operational conditions. Submerged in the towing tank at a carefully selected depth, the nacelle undergoes continuous monitoring of electric power consumption. This data, coupled with sophisticated analysis techniques, facilitates the derivation of crucial hydrodynamic characteristics.

7. Repeated Dry Dynamometer Characterization with Magnetic Coupling (Chapter 6):
The dry dynamometer characterization process is reiterated, this time incorporating magnetic coupling to enhance the reliability and integrity of the experimental setup.

8. Nacelle Redesign and Construction (Chapter 7):
Identification of significant design improvements leads to the incorporation of magnetic coupling to prevent shaft connection leakage. Consequently, the nacelle is reengineered to be compatible with the magnetic coupling system.

9. Repeated Test Procedure (Chapter 8):
The test procedure is repeated, accounting for design improvements and the inclusion of magnetic coupling in the nacelle, ensuring a thorough examination of the hydrokinetic turbine's performance.

Significance of the Proposed Methodology:
The proposed methodology aspires to establish a standardized and verifiable procedure for hydrokinetic turbine testing. By integrating principles from naval architecture and adapting them to the unique challenges of underwater turbine testing, this comprehensive approach ensures the robustness, repeatability, and capacity to yield valuable insights into the hydrodynamic performance of hydrokinetic turbines. Ultimately, this methodology advances the field of ocean current energy conversion technologies, paving the way for sustainable and efficient underwater energy solutions.
2. Chapter 2: Methodology

2.1. Overview of the Proposed Methodology
The proposed methodology is designed to facilitate dynamometer testing of underwater turbines, similar to the well-established testing methods used for wind turbines. In this context, hydrokinetic turbines harness the kinetic energy of water currents, like how wind turbines capture energy from air currents.

The central objective of this methodology is to enable the comprehensive testing and experimentation necessary for the research and development of hydrokinetic turbines. To achieve this goal, the methodology draws inspiration from naval architecture practices, specifically the use of towing tanks, which are commonly employed to evaluate ship designs and estimate hydrodynamic resistance and propulsion power requirements.

The proposed methodology aligns closely with the guidelines suggested by the International Towing Tank Conference (ITTC).

The proposed methodology aims to establish a standardized and verifiable procedure for hydrokinetic turbine testing. It draws from established principles in naval architecture while incorporating specialized adaptations for the unique requirements of underwater turbine testing.

This comprehensive approach ensures that the testing process is robust, repeatable, and capable of yielding valuable insights into the hydrodynamic performance of hydrokinetic turbines, ultimately advancing the field of ocean current energy conversion technologies.

2.2. Adaptation of Towing Tank for Turbine Testing
The towing tank is a specialized laboratory facility utilized for conducting hydrodynamic tests on various models, including ships, offshore structures, and hydrokinetic turbines. The towing tank at the University of New Orleans is a rectangular basin with specific dimensions: it is 30.8 meters long, 4.6 meters wide, and 2.4 meters deep as shown in Fig. 2.1.

![Fig.2.1. UNO towing tank dimensions.](image-url)
The tank is equipped with a carriage system that runs along rails installed along the length of the tank. This carriage system is driven by a cable and a 10 HP AC motor, capable of accomplishing a maximum speed of 3.66 meters per second. The speed of the carriage can be digitally controlled utilizing an electric-powered horizontal planar motion system (PMM). The main purpose of the carriage system is to support and tow the hydrokinetic turbine model during the testing process. The model is mounted on a structure that can be adjusted concerning depth, angle, and orientation comparative with the water stream. This customizability allows us to study the turbine's performance under different working conditions.

![Fig. 2.2. UNO towing tank](image)

The model is associated with the carriage system utilizing cables and pulleys, enabling it to be towed at various speeds and angles to simulate different water stream conditions. To maintain consistent testing conditions, the towing tank is equipped with a filtration and treatment systems. Consequently, water circulates within the tank and ensures that any pollutants are eliminated. Moreover, the water temperature and salt concentration are observed and controlled to maintain exact and reliable testing conditions.

### 2.3. Selection of Scale Model

Towing tanks, which offer a controlled setting for examining fluid flow patterns around propellers under various operational conditions, are frequently employed in research to gain deeper insights into propeller hydrodynamic behaviors. However, testing large-scale propellers at their full size can be both costly and logistically challenging. To assess hydrodynamic performance within a laboratory setting, the practical approach is to downsize the model while preserving its similarity
to the full-scale counterpart. The scaling-down method is discussed in details in [69-78]. This scaling-down process was achieved by considering an important parameter called the advance ratio. The advance ratio, denoted as $J$, is a crucial factor in hydrodynamics and turbine design. It is calculated by comparing the actual distance a propeller or turbine moves through a fluid ($V$) to the theoretical distance it would travel in one revolution at its current rotational speed ($n \times D$), where, $V$ represents the free stream velocity of the fluid, $D$ stands for the diameter of the propeller or turbine, and $n$ represents the rotational speed of the propeller in revolutions per second (rev/s). By using this advance ratio, your coworker determined how to properly scale down the dimensions of the hydrokinetic turbine model. This scaling process ensures that the model retains a similarity to the full-scale turbine while allowing for practical laboratory testing in a towing tank. It's a critical step in experimental research as it enables us to study the hydrodynamic performance of the turbine under controlled conditions, even when working with smaller-scale models.

2.4. Instrumentation and Sensors

2.4.1. Power Supply

A variable DC voltage source model TXLN 150-112 is used as shown in Fig. 2.3. This is a power supply that can provide a variable direct current (DC) voltage to the connected motor. The voltage can be adjusted, allowing for precise control over the motor's rotational speed. By changing the input voltage supplied to the prime mover motor, we can effectively adjust its rotational speed. In DC motors like the PMDC motor, the speed is directly proportional to the voltage applied. Lower voltage results in slower speed, while higher voltage leads to faster rotation. This is the specific type of power supply used in our setup. It's a switching power supply from the TXLN 150-112 series with a power rating of 150 Watts. It's capable of converting alternating current (AC) input voltage, within the range of 85-264 AC (at a frequency of 47-63 Hz), into a stable direct current (DC) output voltage of 12 volts. It's important to note that the total output power of this power supply must not exceed 150 Watts at its maximum output. This limitation ensures that the connected motor and the power supply operate within their specified power limits and do not exceed their rated capacity.
2.4.2. NI SCXI-1000 (LabVIEW) System

This is a system designed to collect, monitor, and record various parameters related to the experimental setup. It is used to monitor system parameters such as current and voltage on both the power and load circuits. The data acquisition system is equipped with multiple sensors. These sensors are specialized devices designed to measure specific physical quantities. The monitoring system is responsible for overseeing and tracking the measurements from the sensors. It provides a way to observe these measurements in real-time. Fig. refers to the specific hardware and software components used for data acquisition and monitoring. "NI" stands for National Instruments, a company known for its measurement and automation products. The "SCXI-1000" is a model associated with the data acquisition hardware. "LabVIEW" is software developed by National Instruments for designing and implementing control, measurement, and data acquisition systems. The data acquisition system collects analog signals, which are continuous and represent variations in physical quantities (e.g., voltage and current) over time. These signals are sampled by the system at specific intervals to create a digital representation of the data. The collected data is displayed on an LCD (Liquid Crystal Display) screen. This provides a real-time visualization of the measured parameters, allowing operators and researchers to monitor the system's performance as the experiment progresses. In addition to real-time display, the system also stores the collected data. This data storage feature is crucial for later analysis, as it allows you to review and analyze the measurements after the experiment is completed.
2.4.3. Futek TRS605
This is a specialized sensor designed for measuring torque (rotational force) in a non-contact manner. It's specifically used for shaft-to-shaft applications, meaning it can measure the torque transferred between two rotating shafts without requiring direct physical contact. The primary function of this sensor is to measure the torque being applied to the rotating shafts in the experimental system. Torque is a crucial parameter when assessing the mechanical behavior of a system. It tells you how much rotational force is being exerted on the shafts. Additionally, this sensor is equipped with an encoder. An encoder is a device that converts shaft rotation into digital signals, allowing you to precisely measure the rotational speed of the system. It provides information about how fast the shafts are rotating. The combined functionality of this sensor (measuring torque and rotational speed) provides valuable data about the system's performance. By measuring torque, we can assess the amount of force being applied, which is essential for understanding power consumption and mechanical behavior. The encoder's rotational speed measurement is crucial for calculating power and assessing the system's dynamics. In summary, the TRS605 non-contact shaft-to-shaft rotary torque sensor with an encoder shown in Fig. 2.5. is employed to measure the torque applied to rotating shafts in your system without physical contact. Additionally, it provides data on the rotational speed of the system. This sensor is essential for
monitoring and analyzing the mechanical performance of your experimental setup, allowing you to make informed decisions and optimizations based on the measured data.

Fig. 2.5. Rotary torque sensor.

2.4.4. Safety System
The Arduino Mega as shown in Fig. 2.6. is a versatile microcontroller board that is commonly used for various applications. In this project, it serves as the central component for developing and controlling the safety system. The primary purpose of this safety system is to monitor the conditions within our setup, specifically focusing on two parameters: temperature and humidity.
The safety system is programmed to measure the temperature of the motor. This measurement helps ensure that the motor does not exceed safe temperature limits during operation. If the motor's temperature rises above the expected or safe level, it could indicate a potential issue, such as overheating. Additionally, the system also monitors the humidity level within the nacelle. The nacelle is designed to be a watertight enclosure, and higher humidity levels could be indicative of moisture or leakage inside the nacelle, which could potentially be problematic. If the safety system detects that either the motor's temperature or the nacelle's humidity exceeds the predefined safe thresholds, it triggers an alarm mechanism. In this case, the alarm mechanism consists of a buzzer shown in Fig. 2.7.
The Arduino sends a voltage signal to the buzzer, effectively activating it. When the buzzer is activated, it produces an audible sound, serving as an alarm signal. The audible alarm serves as a clear and immediate signal that there is a problem or an unusual condition in the system. This prompt notification allows for timely action to address the issue and prevent any potential damage or safety hazards.

2.4.5. Spider Coupling
The motor shaft is the initial point of power generation. The longer shaft is an extended rod or bar that serves as an extension of the motor shaft. It extends further from the motor and typically reaches the location where the propeller is installed. This longer shaft is necessary to bridge the gap between the motor and the propeller, allowing the rotational energy generated by the motor to be transmitted to the propeller vice versa. A spider coupling as shown in Fig. 2.8., also known as
a jaw coupling, is a type of flexible coupling used to connect two shafts together. It consists of two hubs (one attached to each shaft) and a flexible spider element situated between the hubs. The spider element is typically made of an elastomeric material. The spider coupling serves several essential purposes in this context. It accommodates a certain degree of misalignment or angular deviation between the motor shaft and the longer shaft. This is crucial because perfect alignment is often challenging to achieve in real-world applications. The flexibility of the spider element allows for some deviation without causing excessive stress on the shafts or the coupling itself. The elastomeric spider element can absorb and dampen vibrations and shocks that may occur during motor operation. This helps protect both the motor and the connected components, including the longer shaft and the propeller, from the potentially damaging effects of vibrations. The spider coupling efficiently transmits torque from the motor shaft to the longer shaft. As the motor shaft rotates, it applies torque to the coupling's hub, which, in turn, transmits this torque to the longer shaft. This torque transmission is essential for driving the propeller. The flexibility of the spider coupling allows for some radial, angular, and axial movement between the two connected shafts. This flexibility can help mitigate stress and wear on the shafts and the coupling, increasing their longevity.

![Spider coupling](image)

Fig.2.8. Spider shaft coupling.

2.4.6. Thrust Bearing
A thrust bearing shown in Fig. 2.9. is a type of bearing designed to handle axial loads, which are forces applied along the axis or in the direction of the shaft. Unlike radial bearings, which primarily
support radial (perpendicular to the axis) loads, thrust bearings are specialized to support axial loads. The thrust bearing is incorporated into the mechanical system to serve several important functions. It is specifically designed to counteract and support axial or inline loads. When axial forces are applied to the shaft, the thrust bearing distributes and manages these loads, preventing them from causing excessive stress or damage to the shaft. Bearings, including thrust bearings, are engineered to minimize friction between moving components. This reduces wear and heat generation, contributing to the overall efficiency and longevity of the system. Thrust bearings can help maintain the proper alignment of the shaft, preventing it from deviating or buckling under axial loads. They evenly distribute the axial load across the bearing's surface, ensuring that no single point or area of the shaft experiences excessive stress.

Fig. 2.9. Thrust bearing.

2.4.7. Radial Bearing
Our system includes a shaft that is notably long. A long shaft can be prone to certain challenges, including flexing or bending due to its length, especially when subjected to external forces or loads. Radial bearings shown in Fig. 2.10., also known as journal bearings, are designed to support radial
loads, which are forces applied perpendicular to the axis of rotation. These bearings are commonly used to support rotating shafts by minimizing friction and providing stability. The primary objective of incorporating radial bearings along the lengthy shaft is to prevent misalignment. Misalignment can occur when the shaft deviates from its intended path or axis. This can lead to issues such as increased friction, wear, vibration, and reduced efficiency. By securing radial bearings at specific intervals along the length of the shaft, we provide stable points of support. These bearings help maintain the shaft's alignment and prevent it from flexing or bending excessively, even when subjected to external forces or loads. Radial bearings also play a role in distributing the load evenly across the length of the shaft. This ensures that no single section of the shaft bears an undue amount of stress, which could result in deformation or misalignment.

![Radial bearing](image)

**Fig.2.10. Radial bearing.**

### 2.4.8. Voltage Detector Module

In our system, it is necessary to measure the voltage. Voltage is a fundamental electrical parameter that represents the electric potential difference between two points in an electrical circuit. A voltage sensor is a specialized device designed to measure voltage accurately and convert it into a signal that can be read or processed by other components or instruments. The Walfront voltage sensor shown in Fig. 2.11., is described as an analog sensor. Analog sensors provide continuous voltage or current output that varies proportionally with the measured parameter (in this case, voltage).
The output is not in digital form but rather as an analog signal, often in the form of a voltage or current level. The sensor is capable of measuring DC voltage up to 25 volts. This defines the upper limit of the voltage range that the sensor can accurately measure.

![Voltage Sensor](image)

Fig. 2.11. Voltage sensor.

2.4.9. Current Sensor ACS712-20
In our application, it is necessary to measure electrical current. Electrical current is the flow of electric charge through a conductor and is typically measured in units such as amperes (A). The ACS712 shown in Fig. 2.12., is a specific type of current sensor. It is designed to accurately measure electrical current and provide an output that can be used to monitor or analyze the current passing through a circuit. The ACS712 current sensor is used to fulfill the need for measuring electrical current within the system. This sensor is selected for its ability to provide precise current measurements, making it suitable for a wide range of applications where current monitoring is essential. Like the voltage sensor mentioned in 2.4.8., the ACS712 current sensor is an analog sensor. Analog sensors produce a continuous output signal that varies proportionally with the measured parameter (in this case, electrical current).
2.4.10. Amphenol T9602
It is essential to monitor two environmental parameters e.g., temperature and humidity. The Amphenol T9602 shown in Fig. 2.13., is a specific type of sensor designed to measure both temperature and humidity. It is a versatile sensor capable of providing accurate readings for these two parameters. The noteworthy feature of the Amphenol T9602 sensor is that it can function in two modes: Digital Mode (in this mode, the sensor provides digital output), and Analog Mode (in this mode, it produces analog signals that vary proportionally with the measured temperature and humidity).
2.4.11. Temperature & Humidity Sensor DHT11

We have a safety system integrated into our setup. A safety system is designed to monitor motor temperature and nacelle humidity to ensure the safe operation of the equipment or environment. Arduino microcontrollers are primarily designed to interface with digital sensors, which provide data in a discrete, binary format (0s and 1s). The DHT11 shown in Fig. 2.14., is a specific type of sensor designed to measure temperature and humidity. It is classified as a digital sensor because it provides digital output. In the case of the DHT11, it communicates temperature and humidity data in a digital format that can be easily read and processed by the Arduino. This decision aligns with the Arduino's compatibility with digital sensors. The DHT11 provides a straightforward way to monitor temperature and humidity in a digital format, making it suitable for use with Arduino microcontrollers.
2.4.12. Variable Resistor
A variable resistor shown in Fig. 2.15., also known as a potentiometer or pot, is an electronic component designed to adjust the resistance in an electrical circuit. It typically consists of a resistive material in the form of a rod or strip, with a movable contact (wiper) that can be adjusted along its length. By changing the position of the wiper along the resistive element, you can vary the resistance value in the circuit. Moving the wiper closer to one end of the resistor reduces resistance, while moving it closer to the other end increases resistance. In the dry test setup, the variable resistor is used to apply different levels of resistance to the motor. The motor experiences this resistance as a load. When more resistance is introduced into the circuit (by moving the wiper away from one end of the resistor), it becomes harder for the motor to overcome this resistance, and it has to work harder to maintain its rotation. The method of adjusting the resistance in the variable resistor allows us to finely control the amount of load applied to the motor. This load can simulate various operating conditions that the motor might encounter in our application. The use of a variable resistor is essential for assessing how the motor performs under different load conditions without actually connecting it to a physical load or mechanical system. This allows us
to gather valuable data about the motor's behavior, efficiency, and response to varying loads in a controlled environment.

Fig. 2.15. Variable resistor.

2.4.13. Prusa 3D Printer
3D printing is an additive manufacturing process that builds three-dimensional objects layer by layer. It allows you to create physical objects from digital design files. This technology is widely used for rapid prototyping, custom manufacturing, and producing complex shapes that may be challenging to achieve with traditional manufacturing methods. Prusa is a well-known brand in the field of 3D printing. This printer (Prusa i3 MK3S+) shown in Fig. 2.16., is available in Naval Architecture and Marine Engineering Department in the University of New Orleans has been utilized to produce various components or parts.
2.4.14. 3D Printer Material
When 3D printing parts, the choice of material is a critical consideration. Different materials offer various properties and characteristics that can significantly impact the performance and durability of the printed parts. Polyethylene terephthalate glycol (PETG) is a type of thermoplastic filament commonly used in 3D printing. It is a popular choice for several reasons. PETG is known for its excellent durability and impact resistance. It can withstand mechanical stress and is less prone to cracking or breaking, making it suitable for parts that need to endure wear and tear. PETG exhibits
a degree of flexibility, which can be advantageous for parts that may experience bending or deformation without permanent damage. It has good resistance to chemicals and moisture, making it suitable for applications where exposure to liquids or chemicals is a concern.

![PETG filament](image)

**Fig. 2.17.** PETG filament.

2.4.15. Electro-machine

Blade Element Momentum (BEM) theory is a well-known technique used to analyze the performance of turbines. In this study, an in-house BEM code written in Matlab was utilized to consider the specific fluid conditions and rotor characteristics. The BEM code enabled the
estimation of various parameters such as differential torque, thrust, and power for the turbines under investigation.

To validate the predictions obtained from the BEM code and conduct proof-of-concept testing, a small-scale three-bladed horizontal underwater turbine was developed [69-78]. Utilizing a small-scale turbine is a cost-effective approach compared to full-scale testing. This small-scale turbine served as a prototype for testing and numerical model verification.

For the experimental setup, an electrical system was required to meet the necessary requirements and measure the generated power. Ocean current turbines (OCT) generate power based on local forces, primarily the lift force acting on the rotor blades. In addition, to prevent any structural damage to a full-scale prototype, the undesirable forces acting on the carriage were taken into consideration.

To estimate the nominal generated power at different carriage speeds and rotor blade rotational speeds, a method was employed. The carriage speed was used to mimic the motion of the water current, which contains kinetic energy. The tip speed ratio was adjusted to achieve optimal power production at a constant carriage speed. This adjustment was accomplished by varying the rotational speed of the rotor blades.

The apparatus system design was divided into two subsystems: the motor power supplier and the generator power production. The motor drive power supply was responsible for converting the AC line voltage into a DC bus voltage using a switch-mode power supply. By regulating the duty cycle, the output voltage could be controlled, allowing the rotational speed of the DC motor to be varied. Prior to the design process, several considerations needed to be addressed. It was crucial to define the expectations for the entire system and determine the best approach for assembling the system with the required components. Due to the limited carriage speed in the UNO towing tank, the DC machine needed to reach steady-state reference rotational speeds before functioning as a generator. Therefore, electricity was supplied to the motor using a power supplier to achieve the desired speed. Additionally, each circuit element within the system had to be carefully selected and sized to ensure appropriate operation.

By incorporating these considerations and implementing the described methodology, the study aimed to develop an appropriate design and gather the necessary data for further analysis and evaluation of the ocean current turbine's performance.

In order to fully understand and analyze the behavior of an electro-machine, it is important to develop a comprehensive electromechanical model that precisely captures its characteristics in both motor mode and generator mode. This model serves as a fundamental requirement for studying the machine's performance and conduct. One approach to determining the characteristics of the electro-machine is through numerical analysis using computer simulation. By creating a numerical model of the machine and simulating its operation under various conditions, we can obtain valuable insights into its electromechanical way of behaving. Computer simulations allow us to study the machine's performance, efficiency, torque-speed characteristics, and other significant parameters. Additionally, to validate the accuracy of the numerical analysis and simulations, it is crucial to compare the simulation results with experimental data collected from the same electro-machine operating in both motor mode and generator mode. This comparison helps in confirming the model's predictive capabilities and ensures that it accurately represents the present behavior of the machine.

By combining numerical investigation, computer simulations, and experimental data, we can develop an extensive comprehension of the machine's electromechanical characteristics. This
knowledge is vital for optimizing the machine's performance, designing control strategies, and making informed decisions regarding its practical applications. The fundamental principle of induction allows DC motors to work as generators. When a DC motor operates as a generator, the movement of a conductor in a magnetic field induces a voltage across the conductor. In this case, the induced voltage is directly proportional to the speed of the motor's shaft. The induced voltage generated by a DC motor used as a generator can be harnessed and utilized. This principle finds practical applications in regenerative braking of electric vehicles and renewable energy systems, where energy regeneration or recovery is desired. This relationship holds true when the generator is not connected to an external load.

\[ V_{\text{ind}} = \frac{\omega}{K_s} \]  

(2.1)

where \( V_{\text{ind}} \) is the generated voltage (V), \( \omega \) is the motor shaft speed (rpm), \( K_s \) is the speed constant of the motor, aka, speed equation constant (rpm/V). The speed constant is the inverse of the motor voltage constant (\( K_v \)).

\[ K_s = \frac{1}{K_v} \]  

(2.2)

When a DC generator is loaded with current, the induced DC voltage at its terminals will be reduced due to the presence of motor resistance. The motor resistance causes a voltage drop across the internal components of the generator, which reduces the voltage available at the terminals. Hence, we can rewrite equation (2.1) as follows

\[ V_t = \frac{\omega}{K_s} - R_m \cdot I_t \]  

(2.3)

where \( V_t \) is the generated voltage (V), \( \omega \) is the motor shaft speed (rpm), \( K_s \) is the speed constant of the motor (rpm/V), \( R_m \) is the motor resistance (\( \Omega \)), \( I_t \) is the current that goes through the wire (A).

To analyze the characteristics of a generator, we can plot a voltage-current line or curve using an equation that describes the relationship between the generated voltage and the load current. The maximum possible generated voltage is achieved when there is no load current flowing through the generator, which is also known as an open circuit condition. At this point, the generator is not connected to any external load, allowing the maximum voltage to be generated. Conversely, the maximum load current corresponds to the no-voltage induction condition, also known as a short circuit. In this situation, the generator is connected directly to a load with minimal impedance, causing the induced voltage to drop to zero. At this point, the maximum current flows through the generator. By plotting the voltage-current line, we can visualize the generator's behavior and determine its operational limits. The line can help identify the generator's voltage regulation capabilities, efficiency, and optimal operating points for different load conditions. Therefore, the maximum load current is

\[ I_{t,\text{Max}} = \frac{\omega}{K_s} \cdot R_m \]  

(2.4)

The torque to drive the generator in order to overcome the generator internal losses and produce the load current is given by equation (2.5).
\[ \tau = K_t \ast (I_l + I_0) \]  

(2.5)

where \( \tau \) is the required driving torque (Nm), \( I_l \) is the current through the wire (A), \( I_0 \) is the motor no-load current (A) corresponding to the internal torque losses, \( K_t \) is the motor torque constant or motor constant (Nm/A). The torque constant is equal to the motor voltage constant (\( K_e \)).

\[ K_t = K_e \]  

(2.6)

The generator power consists of two different parts, electrical output power and mechanical input power. The electrical output power can be calculated using equation (2.7).

\[ P_e = V_t \ast I_l \]  

(2.7)

where \( P_e \) is the electrical power (W), \( V_t \) is the generated voltage (V), \( I_l \) is the load current (A).

The maximum electrical output power at a given speed can be found from

\[ P_{eMax} = \frac{\pi}{30000} \ast \frac{\omega^2}{4} \ast \left( \frac{\Delta\omega}{\Delta\tau} \right)^{-1} \]  

(2.8)

where \( P_{eMax} \) is the largest electrical output power (W), \( \omega \) is the motor shaft speed (rpm), \( \left( \frac{\Delta\omega}{\Delta\tau} \right) \) is the motor speed-torque gradient (rpm/Nm).

Similarly, the mechanical input power can be calculated using equation (2.8).

\[ P_m = \frac{\pi}{30} \ast \omega \ast \tau \]  

(2.9)

where \( P_m \) is the mechanical power (W), \( \omega \) is the motor shaft speed (rpm), \( \tau \) is the driving torque (Nm).

In general, efficiency is described as the ratio of useful output to total input. Hence, the generator efficiency is measured as the ratio of electrical output power to mechanical input power.

\[ \eta_g = \frac{P_e}{P_m} \]  

(2.10)

where \( \eta_g \) is the generator efficiency (1), \( P_e \) is the electrical power (W), \( P_m \) is the mechanical power (W).

When a machine operates as a generator, the efficiency of the generator follows a comparative way of behaving to its motor efficiency. Typically, a generator tends to achieve higher efficiency at higher rotational speeds. This implies that when the machine works at a faster rotational speed, it is more proficient in converting mechanical power into electrical power. Higher speeds often result in reduced losses and improved efficiency. Nonetheless, it's critical to note that the maximum efficiency of the generator occurs at a lower load current, while maintaining a given rotational speed. In other words, the generator operates most efficiently when the load associated to it draws a lower current. At lower load currents, the losses within the generator are minimized, allowing
for a higher overall efficiency. Designing systems that operate the generator at higher rotational speeds while considering the appropriate load conditions can assist maximize overall efficiency and energy conversion.

In a permanent magnet DC (PMDC) motor, the speed of the motor can be constrained by adjusting the input voltage provided to the motor. By varying the motor voltage, we can control its rotational speed. The relationship between the angular speed (rotational speed) of the PMDC motor and the input voltage can be determined by examining the equivalent circuit of the motor. The equivalent circuit provides a simplified representation of the motor's electrical characteristics. The equivalent circuit of a PMDC motor typically consists of a voltage source, an internal resistance, and an inductor. In summary, the choice of a PMDC motor for the scaled turbine is based on its simplicity, which makes it easier to analyze and work with in the research.

The system equation of a PMDC motor is given by applying Kirchhoff’s voltage law

\[ E_a = R_a i_a(t) + L_a \frac{d}{dt} i_a(t) + E_b \]  \hspace{1cm} (2.11)

where \( E_a \) is the applied voltage [V], \( R_a \) is the terminal resistance [\( \Omega \)], \( i_a \) is the armature current [A], \( L_a \) is the terminal inductance [H], and \( E_b \) is the back electromotive force [V]. Further system equations are

\[ E_b = K_e \omega(t) \]  \hspace{1cm} (2.12)

where \( K_e \) is the back-emf constant [V/rad/s], and \( \omega \) is the angular speed [rad/s].

\[ T = K_T i_a(t) = b \omega(t) + J \frac{d\omega(t)}{dt} \]  \hspace{1cm} (2.13)

where \( T \) is the generated torque [Nm], \( K_T \) is the torque constant [Nm/A], \( b \) is the motor friction coefficient, e.g., brushes [Nm], and \( J \) is the load and armature inertia [kgm\(^2\)].

\[ \frac{d\theta(t)}{dt} = \omega(t) \]  \hspace{1cm} (2.14)

where \( \theta \) is the rotor angular position [rad].

In the case of a constant operating point, equation (2.11) can be simplified as follows

\[ E_a = R_a i_a + E_b \]  \hspace{1cm} (2.15)

Thus, the electrical input power can be calculated by multiplying voltage by current

\[ E_a i_a = R_a i_a^2 + K_e \omega i_a \]  \hspace{1cm} (2.16)
Mechanical output power is equal to torque times rotational speed

\[ T\omega = K_T i_a \omega \]  

(2.17)

Electrical losses are caused by the resistance in the circuit

\[ Losses = R_a i_a^2 \]  

(2.18)

The choice of an appropriate motor is a critical aspect of our project. This decision is influenced by simulation work that was conducted to assess the motor's suitability for our specific application. A PMDC motor type Maxon DCX 35 L was chosen. DCX signifies that it's a direct current (DC) motor with permanent magnet components, and 35 L refer to its specific size. The selected 12V PMDC motor has a power rating of 80/120 Watts. The rotational speed of the PMDC motor can be adjusted by changing the input voltage provided to the motor. By varying the voltage, you can control the motor's speed, allowing for flexibility in its operation. The PMDC motor has a characteristic speed rate of 8130 RPM (Revolutions Per Minute). This is the motor's rotational speed under specific operating conditions, typically at its rated voltage and load. To adapt the motor's speed to the requirements of our scaled-down turbine, a planetary gearhead is incorporated. The GPX 37 denotes the model of gearhead used. Planetary gearheads are known for their compact size and efficient speed reduction capabilities. The planetary gearhead has a reduction ratio of 16:1. This means that for every 16 revolutions of the motor, the output shaft of the gearhead rotates once. In other words, the gearhead reduces the motor's speed by a factor of 16, making it more suitable for our scaled-down turbine's requirements.

Fig. 2.18. Maxon 12V PMDC motor.
In order to develop a model based on these equations, the values of the motor parameters must be defined. Simulations have been performed for the PMDC motor using the motor parameters shown in Table 2.1. The models were implemented in a MATLAB environment.

<table>
<thead>
<tr>
<th>Motor Data</th>
<th>unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Voltage</td>
<td>V</td>
<td>12</td>
</tr>
<tr>
<td>No Load Speed</td>
<td>rpm</td>
<td>8130</td>
</tr>
<tr>
<td>No Load Current</td>
<td>A</td>
<td>0.32</td>
</tr>
<tr>
<td>Speed Constant</td>
<td>rpm/V</td>
<td>699</td>
</tr>
<tr>
<td>Torque Constant</td>
<td>Nm/A</td>
<td>0.0137</td>
</tr>
<tr>
<td>Motor Resistance</td>
<td>Ω</td>
<td>0.079</td>
</tr>
<tr>
<td>Rotor Inertia</td>
<td>gcm²</td>
<td>99.5</td>
</tr>
<tr>
<td>Braking Load Resistance</td>
<td>Ω</td>
<td>1</td>
</tr>
<tr>
<td>Load Torque</td>
<td>Nm</td>
<td>0.12</td>
</tr>
</tbody>
</table>

2.4.16. Motor Driver

2.4.16.1. Fuzzy Logic Control with Arduino
Initially, by adopting a fuzzy logic control approach with the assistance of an Arduino, the speed of the PMDC motor was regulated. These instructions governed how the fuzzy logic control, implemented via the Arduino, regulated the PMDC motor's speed.

DC motors are used in a multitude of industrial applications due to their simplicity, economical cost, and uncomplicated drives. PMDC motors have a long tradition of use as adjustable speed machines since they possess advantages over conventional DC motors, e.g., no need for an excitation current, low noise operation, relatively low weight to torque ratio, and high efficiency. A block diagram of the PMDC motor is shown in Fig. 2.19.

![Block diagram of PMDC motor.](image)

Fig. 2.19. Block diagram of PMDC motor.
The input voltage source, $E_a(s)$, is applied to the PMDC motor, and the angular speed $\Omega$ is the output of the system. The system equations are as follows

$$E_a(s) = sL_a I_a(s) + R_a I_a(s) + E_b(s)$$  \hspace{1cm} (2.19)

where $E_a$ is the applied voltage [V], $I_a$ is the armature current [A], $L_a$ is the terminal inductance [H], $R_a$ is the terminal resistance [\Omega], and $E_b$ is the back electromotive force [V].

$$E_b(s) = K_e \Omega(s)$$  \hspace{1cm} (2.20)

where $K_e$ is the back-emf constant [V/rad/s], and $\Omega$ is the angular speed [rad/s].

$$T_M(s) = K_T I_a(s)$$  \hspace{1cm} (2.21)

where $T_M$ is the generated torque [Nm], and $K_T$ is the torque constant [Nm/A].

$$T_M(s) - T_f(s) = sJ \Omega(s) + B \Omega(s)$$  \hspace{1cm} (2.22)

where $T_f$ is the load torque [Nm], $B$ is the motor friction coefficient, e.g., brushes [Nms], and $J$ is the load and armature inertia [kgm$^2$].

Thus, the PMDC motor can be modeled for controlling speed purposes by the following transfer function

$$\frac{\Omega(s)}{E_a(s)} = \frac{K_T}{(sL_a + R_a)(sJ + B) + K_e K_T}$$  \hspace{1cm} (2.23)

To develop a model based on equation (2.23), the values of the motor parameters must be defined. Simulations have been performed with the PMDC motor using the motor parameters shown in Table 1. The models were developed in a MATLAB environment.

Conventional control algorithms are designed with fixed structure and parameters. This causes significant problems in the non-linear region of DC motor operation. Hence, tuning and optimization of these drives is challenging and highly depends on the accuracy of the system models and parameters. Based on the nature of the turbine operation, load dynamics will change frequently due to the variation in current speed. Thus, it is essential to develop an intelligent technique to improve performance in the presence of non-linearity along with enhancing the robustness of speed control design. Fuzzy logic controllers (FLC) are designed particularly for non-linear dynamic systems which consists of complex inputs and outputs with impractical ways to develop their mathematical models. FLCs are derived from the input fuzzy set (fuzzification module), fuzzy logical rules, an inference engine, and an algorithm of output computation (defuzzification module). Fig. 2.20. shows the block diagram of a FLC.
The system's dynamic variables are given as input signals to the fuzzy controller. Our drive was developed in such a way as to adjust motor voltage $E_a$ based on the input variables, speed error $e$, and changes in speed error $\dot{e} = \frac{de}{dt}$. Triangle membership functions for input variables convert the input errors into fuzzy sets. Linguistic fuzzy sets are defined as follows:

- NH: Negative High
- PH: Positive High
- NL: Negative Low
- PL: Positive Low
- NM: Negative Medium
- PM: Positive Medium
- ZE: Zero

The triangle membership functions convert the input errors $e$, and $\dot{e}$ into fuzzy variables $\mu(e)$, and $\mu(\dot{e})$ by assigning each of these to 7 fuzzy sets. Fig. 2.21. shows the membership function for input speed errors $e$. The input change in speed error $\dot{e}$ membership function is illustrated in Fig. 2.22.
Based on 7 fuzzy sets for each of the input errors, there are 49 corresponding fuzzy rules to be defined in the control rule decision matrix. This fuzzy control decision table is shown in Table 2.2.

**TABLE 2.2: Fuzzy control rules matrix.**

<table>
<thead>
<tr>
<th>Primary Fuzzy Set</th>
<th>NH</th>
<th>NM</th>
<th>NL</th>
<th>ZE</th>
<th>PL</th>
<th>PM</th>
<th>PH</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH</td>
<td>NH</td>
<td>NH</td>
<td>NH</td>
<td>NH</td>
<td>NM</td>
<td>NL</td>
<td>PL</td>
</tr>
<tr>
<td>NM</td>
<td>NH</td>
<td>NH</td>
<td>NH</td>
<td>NM</td>
<td>NL</td>
<td>PM</td>
<td>PL</td>
</tr>
<tr>
<td>NL</td>
<td>NH</td>
<td>NM</td>
<td>NL</td>
<td>ZE</td>
<td>PL</td>
<td>PM</td>
<td>PM</td>
</tr>
<tr>
<td>ZE</td>
<td>NH</td>
<td>NM</td>
<td>NL</td>
<td>ZE</td>
<td>PL</td>
<td>PM</td>
<td>PH</td>
</tr>
<tr>
<td>PL</td>
<td>NM</td>
<td>NL</td>
<td>NM</td>
<td>PL</td>
<td>PM</td>
<td>PH</td>
<td>PH</td>
</tr>
<tr>
<td>PM</td>
<td>NL</td>
<td>NM</td>
<td>PL</td>
<td>PM</td>
<td>PH</td>
<td>PH</td>
<td>PH</td>
</tr>
<tr>
<td>PH</td>
<td>NL</td>
<td>PL</td>
<td>PM</td>
<td>PH</td>
<td>PH</td>
<td>PH</td>
<td>PH</td>
</tr>
</tbody>
</table>

This controller rules are based on these general considerations:
1. If both speed error and speed change error are zero, maintain the current settings.
2. If speed error is approaching zero at an adequate rate, maintain the current settings.
3. If speed error is diverging from zero, change the output signal proportional to input error to move toward zero.

Table 2.3 gives the function definition of the primary fuzzy sets.

**TABLE 2.3: Function definition of primary fuzzy sets.**

<table>
<thead>
<tr>
<th>Primary Fuzzy Set</th>
<th>a</th>
<th>b</th>
<th>c</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH</td>
<td>-</td>
<td>-1</td>
<td>-0.69</td>
</tr>
<tr>
<td>NM</td>
<td>-1</td>
<td>-0.69</td>
<td>0.33</td>
</tr>
<tr>
<td>NL</td>
<td>-0.69</td>
<td>-0.33</td>
<td>0</td>
</tr>
<tr>
<td>ZE</td>
<td>-0.33</td>
<td>0</td>
<td>0.33</td>
</tr>
</tbody>
</table>
The following steps describe the mathematics of the fuzzy logic controller algorithm

**Step 1**
Calculate the normalized speed error and change in speed error:

\[
e(k) = \frac{\omega_{ref}(k) - \omega(k)}{\omega_{ref}}
\]

\[
\dot{e}(k) = G\{e(k) - e(k - 1)\}
\]

where \(e(k)\) is the speed error, \(\omega_{ref}\) is the reference speed, \(e(k - 1)\) is the speed error at the previous instant, and \(G\) is the gain to normalize the error change.

**Step 2**
The triangle membership functions are used to assign the membership grades to each linguistic class by using the following equation

\[
\mu(s; a, b, c) = \begin{cases} 0 & \text{for } x < a \\ \frac{x - a}{b - a} & \text{for } a \leq x \leq b \\ \frac{c - x}{c - b} & \text{for } b \leq x \leq c \\ 0 & \text{for } x > c \end{cases}
\]

where \(a, b,\) and \(c\) are defined in table 3, and \(x\) is either the speed error or the change in speed error.

**Step 3**
The membership grades of the condition can be calculated by using the law of intersection of two fuzzy sets as follows:

\[
\mu(k) = \mu_e(i) \cap \mu_{\dot{e}}(j) = \min\{\mu_e(i), \mu_{\dot{e}}(j)\}
\]

where \(i, j = 1, 2, \ldots, 7\) and \(k = 1, 2, \ldots, 49.\)

**Step 4**
The fuzzy controller output can be selected based on Table 2 and the fuzzy IF, THEN statement, e.g.,

IF \(e\) is \(\alpha\), and \(\dot{e}\) is \(\beta\) THEN controller output \(\mu\) is \(\gamma\).

**Step 5**
Scaling the output membership function can be performed by the following equation:
\[ w(k) = \mu_e(i)\mu_e(j) \]  \hspace{1cm} (2.28)

where \( w \) is the weight associated with the corresponding fuzzy control rule, \( i, j = 1, 2, \ldots, 7 \) and \( k = 1, 2, \ldots, 49 \).

**Step 6**

The crisp value of the output signal can be obtained using the following equation:

\[ E_a = \frac{\sum_{k=1}^{49} \omega(k)\mu(k)}{\sum_{k=1}^{49} \omega(k)} \]  \hspace{1cm} (2.29)

where \( E_a \) is the regulated input voltage.

To examine the performance of the motor drive employing fuzzy logic technique, two identical PMDC motors were mechanically connected shaft to shaft. This connection applies a varying amount of load on one motor: operate one of the PMDC’s as a main mover and one as a generator. In this setup, by adjusting the amount of resistance on the generator side, the load can be varied. Thus, a variable resistor was connected to the generator which could be manually altered. An AC to DC switching power supply type TXLN 150 series was connected to the PMDC motor type DCX 35 L (80/120 Watt). Turbines in general and ocean current turbines in particular run at a very low speed. Our small-scale ocean current turbine runs at a higher speed in comparison with a full-size turbine, however, at a very low speed in comparison to a typical PMDC motor speed ranges. Consequently, the rotational speeds of the PMDC motors were reduced by adding a planetary gearhead type GPX 37 with a reduction ratio of 16:1. As such, the rotational speeds of the PMDC motors were adjusted from 8130 RPM to 508 RPM. A TRS605 non-contact shaft-to-shaft rotary torque sensor with encoder was placed in between these two motors to read out the rotational speed. An Arduino Mega was connected to Simulink to generate a pulse-width modulation (PWM) control signal as a fuzzy logic controller. This PWM signal was provided to an ESCON 50/5 servo controller to adjust the speed of the PMDC motor. This setup is shown in Fig. 2.23.
In the feedback system, the measured rotational speed was provided to the fuzzy logic controller to generate the PWM control signal. The system is described in the block diagram shown in Fig. 2.24.
The rotational speed of the PMDC motor was manually altered by fluctuating the value of the input voltage governed by the servo motor drive, which was adjusted by the PWM signal from the feedback system and fuzzy logic controller. In addition, the size of the load was varied by changing the resistance value of the variable load resistor. The minimum value of the resistance can be obtained having the PMDC power rate and determining the input voltage. The reason for developing this controller rather than using a built-in servo PID controller was that although the PID controller performs reasonably in a dry test lab environment, for towing tank.
experiments which add numerous amounts of complexity into the system, it is essential to run the turbine in a robust mode which does not require a precise, noise-free input. Also, it can be programmed to fail safely with a smooth control function for the output signal despite a wide range of possible input signals.

Fig. 2.25. shows some experimental results under a wide range of angular speed reference step changes. The black dash-dotted line gives the reference speed and the red solid line plots the measured motor speed from experiment under no load conditions. This graph shows good speed tracking by the controller.

Fig. 2.25. Speed vs time at no-load condition.

Fig. 2.26. shows the current passing through the PMDC motor. The same scale has been used for the current at the no-load condition as well as at the maximum power range for comparison. Negative current passed through the circuit due to the back-emf at the time when motor speed was decreasing.
Fig. 2.26. Current vs time at no-load condition.

Fig. 2.27. shows experimental results under the same range of angular speed reference step changes as those in Fig. 2.25. The black dash-dotted line shows the reference speed and the red solid line plots the measured motor speed from the experiment maximum power condition. This condition can be adjusted by reducing the variable resistor at the generator side. This graph shows good speed tracking performed by the controller.
Fig. 2.27. Speed vs time at full-load condition.

Fig. 2.28. shows the current passing through the PMDC motor at maximum power; negative current passed through the circuit due to the back-emf at the time when the motor speed was decreasing. Evidently, more current is drawn from the power source to produce the higher amount of torque required by the generator to generate the higher amount of power due to the lower resistance at the generator side.
Based on the results shown, the speed of the PMDC motor is successfully controlled by using a fuzzy logic controller. The speed tracking shows good agreement with the reference speed, regardless of either the absence or presence of load. However, the fuzzy logic technique introduced too much uncertainty in controlling the PMDC motor's speed. As a result, I decided to try a different approach.

2.4.16.2. Using an Escon 50/5 Servo Controller
The Escon 50/5 servo controller is a specialized electronic device designed to control the speed and position of motors precisely. It's commonly used in applications where accurate control is required. To use the Escon controller effectively, you needed to tune its Proportional-Integral-Velocity (PIV) controller. PIV control is a control algorithm that adjusts the motor's behavior based on feedback from sensors, allowing you to maintain precise control over the motor's speed. Fig. 2.29. illustrates the hardware wiring of the Maxon DC motor with an encoder. This provides a visual representation of how the motor, encoder, and Escon controller are connected and configured.
In essence, we initially attempted fuzzy logic control with the Arduino but encountered uncertainties in controlling the PMDC motor’s speed. Subsequently, we adopted a more precise approach using the ESCON 50/5 servo controller, and the tuning of its PIV controller allowed for better control. The Fig. 2.30 provides a visual reference for how the hardware components are interconnected in this setup.
The ESCON motor driver is equipped with software that offers a user-friendly interface. This software provides an intuitive environment that makes it easy for users to configure and control the motor driver. The software allows for PIV tuning, which is a process of adjusting control parameters to optimize the performance of the motor. PIV tuning is essential for achieving precise control over the motor's speed and response. Once the PIV tuning has been performed using the software, users can easily adjust the motor's speed. This adjustment is typically done by inputting
the desired RPM in the controller tab of the software. The motor driver will then regulate the motor's speed to match the specified RPM.

Fig. 2.31. ESCON servo controller software interface.

The ESCON motor driver offers the capability to provide two analog signals. These analog signals can be collected by a data acquisition system. Data acquisition involves measuring and recording various parameters or signals, in this case, analog signals related to motor speed and current.
3. Chapter 3: Dry Dynamometer Characterization

The main contribution of this work is to determine the characteristic parameters in both modes for the PMDC motor selected to use as a small scale experimental hydrokinetic turbine. To achieve this, the PMDC motor used as a prime mover was mechanically connected shaft to shaft to an identical PMDC motor configured as a generator. A time-varying input voltage was applied to alter the speed of the motor. The speed of the prime mover forced the generator to generate a voltage with different amplitudes corresponding to the prime mover input voltage. On the generator side of the circuit, a variable resistor $R$ was manually altered. The variable resistor acts in the system as a changeable load. The equivalent circuit of this setup is illustrated in Fig. 3.1.

![Fig. 3.1. Equivalent circuit of the experimental setup.](image)

The system behavior of the dynamometer is given by applying Kirchhoff’s voltage law on both circuits knowing that the armature resistor, armature inductance, angular speed, and the amount of the torque are the same.

Power circuit:

$$E_a = R_a i_a(t) + L_a \frac{d i_a(t)}{dt} + K_a \omega(t)$$

(3.1)

Load circuit:

$$E_b = R_a i_b(t) + L_a \frac{d i_b(t)}{dt} + R i_b(t)$$

(3.2)

where $R$ is the variable resistor [$\Omega$] and $i_b$ is the generated current [A].
In the case of a constant operating point, equations (3.1) and (3.2) can be simplified as follows.

Power circuit:

\[ E_a = R_a i_a + K_e \omega \]  \hspace{1cm} (3.3)

Load circuit:

\[ K_e \omega = (R_a + R) i_b \]  \hspace{1cm} (3.4)

In order to determine the performance and efficiency of the PMDC in both motor mode and generator mode, the input voltage, motor parameters, and angular speed are measured. Then by considering equations (3.3) and (3.4), current flowing in both the power and load circuits can be estimated. Thus, having the currents and voltages, input power and generated power can be calculated.

3.1. Experimental Setup

To enhance the accuracy of the estimations regarding generated power and input power from numerical analysis, a specific experimental setup was employed including two identical PMDC motors.

- Connection of PMDC Motors: The two PMDC motors were mechanically connected shaft to shaft. This setup allowed us to not just assess the performance of the PMDC motor as a prime mover (when it drives the turbine) yet additionally as a generator (when it produces electrical power).
- Variable DC Voltage Source: A variable DC voltage source was connected to one of the PMDC motors, known as the prime mover motor (type DCX 35 L with a power rating of 80/120 Watts). By changing the input voltage provided to this motor, its rotational speed is adjusted.
- Gearhead for Speed Adjustment: The PMDC motor has a characteristic speed rate of 8130 RPM. However, due to the fact that the turbine was scaled down in size for experimentation, a planetary gearhead (type GPX 37) with a reduction ratio of 16:1 was utilized. This gearhead reduced the motor's speed to a more suitable level for the scaled-down turbine.
- Rotary Torque Sensor: A TRS605 non-contact shaft-to-shaft rotary torque sensor with an encoder was placed between the prime mover and generator shafts. This allowed us to measure the driving torque applied and the rotational speed of the system.
- Servo Motor Driver: To control the speed of the prime mover PMDC motor, an ESCON 50/5 servo controller was utilized as a regulator. This controller allowed us to fix a setpoint value for the motor's speed, providing precise command over the motor's rotational speed during testing.

The experimental setup, as described above, is visually depicted in Fig. 3.2.
This setup was carefully intended to provide accurate and reliable data for assessing the performance of the hydrokinetic turbine PMDC motor under various conditions. By measuring torque, speed, and controlling the motor's speed with precision, we can obtain valuable insights into the turbine's PMDC motor behavior and efficiency during experimentation. The data acquisition system incorporates sensors that monitor the electrical current and voltage on both sides of the system, namely the power circuit (supplying electrical power to the prime mover PMDC motor) and the load circuit (where the generated power is utilized). These sensors allow us to measure and analyze the electrical characteristics of the turbine during testing.

To alter the speed of the prime mover, the input voltage is manually adjusted to the motor driver. The generator, mechanically connected to the prime mover, was forced to produce a voltage as a result of this connection. Varied load resistor utilized to assess the system's performance under different conditions. However, there is a restriction on the size of the load resistor. At the point when a smaller load resistor is used, the current flowing through the system increased, resulting in higher power output. This relationship between load resistor size, current, and power is a significant consideration for testing the turbine's efficiency and power generation capabilities. The PMDC motor used in the experiment had the power rating modes: 80 Watts in continuous operation mode and 120 Watts in intermittent operation mode. The decision of the specific motor and its power rating modes were likely based on the requirements and characteristics of the hydrokinetic turbine model.
3.2. Experimental and Numerical Analysis Results
The reason for using a PMDC motor with a planetary gearhead combination was because of the slow-moving nature of the driving mechanism in ocean current turbines. The turbine model expected a slower rotational speed to match the characteristics of ocean currents. However, this gearing combination presented difficulties when using the motor as a generator. Reversing the motor to function as a generator caused inefficiencies because the two-stage gearhead is not originally intended for such utilization. As a result, the generator mode may not achieve the same level of efficiency as the prime mover mode, impacting the overall performance and power generation capability of the hydrokinetic turbine.

The Fig. 3.3. shows a comparison between two models: one derived from numerical analysis and the other based on actual measurements from experiments. The difference between the two models can be attributed to a specific factor: the calculations for the numerical analysis were initially performed based on the PMDC motor's parameters without considering the effect of the gearhead reduction. In other words, when running the numerical analysis, the researchers focused on the PMDC motor itself, neglecting the impact of the gearhead that was attached to it. However, in practical experiments, the gearhead's reduction effect becomes significant and needs to be accounted for. The figure illustrates that at lower voltage levels, the measured current from experiments is higher than what was initially predicted by the numerical analysis. The reason for this discrepancy is that, at lower voltages, more current is required to compensate for the losses caused by friction within the gearhead. Friction within the gearhead can result in energy losses, making the actual motor-gearhead system less efficient than predicted by the numerical analysis. As a consequence, a higher current is needed to achieve the expected performance level during the experimental measurements. This observation highlights the importance of considering all components and their interactions in the system when conducting numerical analysis or simulations.
Fig. 3.3. Voltage current plot of power circuit.

Fig. 3.4. presents a correlation between the rotational speed of the PMDC motor, which was operated as a prime mover, under different input voltage conditions. In the figure, the black line represents the rotational speed calculated from numerical analysis, while the red line represents the measured rotational speed obtained from actual experimental testing. The comparison in Fig. 3.4. reveals that the measured angular speed of the experimental PMDC motor is lower compared to the angular speed predicted by the numerical analysis. The reason for this inconsistency is attributed to the presence of the planetary reduction gearhead.
Fig. 3.4. Voltage motor speed plot of power circuit.

Fig. 3.5. shows the generated current of the PMDC motor which was run as a generator versus different voltages. The black line represents the generated current derived from numerical analysis and the red line represents the measured generated current from experiment. There is an anomalous behavior between 1 and 3 Volts, which, can be explained by the larger input power applied to overcome the gearhead frictional losses.
Fig. 3.5. Load circuit voltage current plot.

Fig. 3.6. and Fig. 3.7. show the measured voltage and current of both power and load circuits from experiment. It can be ascertained that there is good agreement between input parameters and generated parameters. The generated parameters have slightly lower values in comparison to those of the input.
Fig. 3.6. Two circuits measured current plot.
Fig. 3.7. Two circuits measured voltage plot.

Fig. 3.8. gives a comparison of the torque delivered by the PMDC motor at different input voltages, alongside the measured torque obtained during experimental testing. In the figure, the black line represents the torque values determined from numerical analysis, while the red line represents the torque values measured during the actual experiment. The comparison in Fig. 3.5. reveals that the measured torque during the experimental testing is different from the torque values estimated by the numerical analysis. The reason for this difference is attributed to the presence of the gearhead attached to the PMDC motor. When operating at lower input voltages, the measured torque is higher than the torque values estimated by the numerical analysis. This is because at lower voltages, the motor requires more current to compensate for the friction losses within the gearhead. As mentioned previously, the gearhead introduces mechanical inefficiencies and losses. These losses impact the actual torque output of the motor during experiments, resulting in a higher measured torque compared to what was initially anticipated in the numerical analysis.
Fig. 3.8. Estimated and measured torque.

Fig. 3.9. shows the measured input power and generated power by the PMDC motors at different voltages. Input power is essentially the product of the measured voltage and current at the power circuit. Similarly, output power is the product of the measured voltage and current at the load circuit.
Fig. 3.9. Measured power.

Fig. 3.10. shows the efficiency of the PMDC motor at different voltages. The efficiency is dramatically low at the low speed because of the large friction losses at the gearheads. This efficiency improves by running at higher speed and reaches 47.8% at 12V (479.4 rpm).
In summary, as it is represented the influence of the gearhead on the performance of the PMDC motor. The presence of the gearhead leads to discrepancies between the estimated values from numerical analysis and the measurements during experimental testing, especially at lower input voltages. Understanding the impact of the gearhead on PMDC motor output is important for accurately assessing the performance of the hydrokinetic turbine model and optimizing its design and efficiency.

Fig. 3.10. Measured efficiency.
Chapter 4: Nacelle Design and Construction

4.1. Design in Solidworks

The hydrokinetic turbine nacelle was developed adhering to the design guideline rules suggested by the International Towing Tank Conference (ITTC). The design cycle was performed utilizing SolidWorks programming, a computer-aided design (CAD) software that allows for precise modeling and visualization. To guarantee the security and integrity of the electronic parts and sensors inside the hydrokinetic turbine model during testing, a decision was made to separate the model into two distinct parts. This partition was executed to protect the delicate parts from expected harm or interference during the testing process.

The first segment of the model is called as the insert, and it basically acts as a defensive housing for the PMDC motor which runs as generator and the sensors utilized for data collection. The insert is made out of two individual pieces: a base piece and a cap. The base piece of the insert is intended to serve as a durable and stable platform for the PMDC motor and sensors. This part guarantees that the motor/generator and sensors are safely situated and held set up during testing. Fig. 4.1 gives a visual representation of how the base piece of the insert looks and functions.

![Solidworks sketch of the insert base.](image)

Moreover, the cap is the upper piece of the insert shown in Fig. 4.2. Its essential job is to cover and protect the instruments housed inside the insert from outside factors that might affect their performance. This incorporates defending the components from potential leakage from the submerge nacelle in the towing tank, which could somehow compromise the exactness and security of the experimental setup.
By utilizing the insert with its base piece and cap, we have established a robust and protective environment for the PMDC motor and sensors. This arrangement ensures that the experimental setup remains reliable and secure during hydrokinetic turbine testing, and assists with the precision and accuracy of the collected data.

The insert that was designed serves a particular purpose in the testing of the hydrokinetic turbine model. Its intended use is to fit securely into a watertight torpedo nacelle illustrated in Fig. 16. The torpedo nacelle acts as a second layer of security for the electronic instruments and sensors contained inside the hydrokinetic turbine model. It is explicitly designed to be completely submerged in water during the testing system. The watertight design of the nacelle guarantees that the components inside the insert stay dry and protected from any water entrance, ensuring their safety and security during testing.
By separating the model into two segments - the insert and the torpedo nacelle - we have introduced several advantages. This division, first and foremost, takes into consideration a less complex and more direct assembly and disassembly process for the turbine model. The insert can be put into the nacelle with ease, and the two sections can be safely sealed together. Also, the division provides an additional layer of insurance for the sensitive electronic parts and sensors within the turbine model in a controlled underwater environment. By placing the insert inside the watertight nacelle, we can ensure that all critical parts are actually isolated from the surrounding water, taking out the risk of damage due to water exposure.

4.2. Print and Assembly

The nacelle, was manufactured utilizing a Prusa i3 MK3S+ 3D printer. The 3D printer used a water-safe plastic material to ensure the nacelle's durability to endure the forces and stresses applied during testing. Polyethylene terephthalate glycol-changed (PETG) filament was selected for 3D printing to construct the hydrokinetic turbine model. PETG is known for its solidity and resilience, making it appropriate for use in harsh environments, like submerged testing situations. 3D printer has a length limitation of 10 cm in all dimensions. This constraint influenced the design strategy. To overcome this limitation, we divided the nacelle into smaller pieces that fit within the printer's size constraints. Fig. 4.4. shows the insert pieces next to each other before removing all the supports materials, and Fig. 4.5. shows the torpedo pieces. Each of the divided nacelle components, including the insert and torpedo, was separately 3D printed. Once all the individual pieces were printed, they were then assembled or glued together to create the final nacelle.
structure. This assembly step allows you to combine the separately printed parts into a cohesive unit.

Fig. 4.4. Printed insert pieces.
After the model was completed, extra steps to reinforce the model and make it watertight were taken. The model was covered with epoxy, a strong adhesive material, to give an additional layer of security against potential water damage during testing. This epoxy coating effectively seals any gaps or openings in the model, preventing water from entering and harming the internal components. The advancement of the hydrokinetic turbine model was done with intense consideration and attention to detail. By utilizing robust materials and adding defensive coatings, we expected to create a durable and dependable turbine model equipped for enduring the afflictions of submerged testing.
The combination of 3D printing technology, PETG filament, and epoxy covering took into consideration the successful development of a solid and watertight hydrokinetic turbine model. This model serves in as an essential device for conducting accurate and reliable testing.
To construct the turbine, the insert component, which houses the motor and sensors, is secured inside the torpedo component. This assembly step likely involves aligning and connecting these two parts to create the complete nacelle structure. The nacelle structure features a torpedo cap located at the end of the nacelle. To secure the nacelle and ensure that it remains intact and watertight, the torpedo cap at the end of the nacelle is attached by screwing it into place. This screwing action involves fastening the cap securely to the nacelle body. Achieving a water-tight seal is crucial for the proper functioning and protection of the internal components within the nacelle. To prevent any potential leakage of water into the nacelle through the connection between the torpedo cap and the nacelle body, a sealing method is employed. By filling any gaps or spaces between the torpedo cap and the nacelle body with wax, we effectively create a seal that helps prevent water from entering the nacelle. Fig. 4.7. shows this step.

![Image of a scaled turbine with wires connected to it.](image)

Fig. 4.7. Torpedo cap and nacelle sealing.

The scaled turbine needs to be securely attached to the towing tank carriage. This attachment is crucial to ensure that the turbine remains in place and functions as intended during testing in the
towing tank. Two pipes are utilized to secure the turbine to the towing tank carriage. These pipes serve a dual purpose:

- **Turbine Securement:** The pipes function as structural supports to hold the turbine in position on the towing tank carriage. They provide stability and prevent the turbine from moving or dislodging during testing.
- **Wire Routing:** Additionally, these pipes serve as conduits for routing wires. The same pipes are used to transmit data collection wires and power wires to the turbine. This simplifies the organization of wires and ensures that they are safely routed without posing a risk to the turbine's operation.

Since the setup involves submerging the turbine in water for testing, it's essential to prevent any water leakage into the pipes or around the turbine connection points. To address this concern, sealing tape is used to the connection points where the pipes meet the turbine. Sealing tape is a commonly used material for creating water-tight seals. It is applied at the junction between the pipes and the turbine to prevent water from seeping into the connection. In addition to sealing tape, the same wax is applied as an additional measure to prevent any potential leakage as shown in Fig. 4.8.

![Fig. 4.8. Pipes connection to the nacelle.](image)
Before proceeding with the testing, we took great care to ensure that our turbine was adequately sealed to prevent water ingress. This is a critical step to protect the internal components of the turbine from water damage during testing. With the turbine's watertight preparations in place, we attached the turbine pipes to the carriage using two clamps. These clamps served as secure fasteners to hold the turbine in position on the towing tank carriage. This step ensures that the turbine remains stable during testing as shown in Fig. 4.9.

![Image of pipes connection to the towing tank carriage](image1)

**Fig. 4.9. Pipes connection to the towing tank carriage.**

The next step involved connecting all the necessary wires to the data acquisition system shown in Fig. 4.10. These wires included data collection wires and power wires. Proper wiring is essential for collecting data from the turbine and providing power to operate it.
Before submerging the turbine into the tank, we conducted several test runs. These test runs involved running the turbine a few times to ensure that all components were functioning correctly. This step allowed us to identify and address any potential issues or malfunctions before the actual testing in the tank.

Fig. 4.10. Data acquisition system and safety system.
After verifying that everything was working properly during the test runs, we proceeded to submerge the turbine into the tank. Submersion is a critical phase of hydrokinetic turbine testing because it replicates real-world conditions where the turbine operates in a water environment.
Overall, the sequence of actions described is demonstrated a systematic and careful approach to preparing, testing, and deploying our hydrokinetic turbine in the towing tank. This methodical process helps ensure the reliability and accuracy of your experimental data and contributes to the success of your research or testing objectives.
5. Chapter 5: Testing Procedure

5.1. Hydrokinetic Turbine Setup
The hydrokinetic turbine model features an electric motor which can be run as a generator, and various sensors. They are all housed inside the insert. Specifically, a PMDC motor of the type DCX 35 L, with a power rating of 80 to 120 Watts, was used as the motor/generator. To control its operation, the PMDC motor was associated with a driver, which allows exact control of the motor's speed. To adjust the motor speed, a variable DC voltage source was connected to the driver. By varying the input voltage to the motor, its rotational speed can be adjusted as desired for the testing purposes. The PMDC motor utilized in the hydrokinetic turbine model has a speed rating of 8130 RPM (Revolution per Minute). However, to suit the scaled-down size of the turbine model, a planetary gearhead of the sort GPX 37 with a reduction ratio of 16:1 was utilized to reduce the speed output of the motor. The decision to employ a gearhead with a reduction ratio was necessary and essential due to the fact that the hydrokinetic turbine model is worked to a more limited rotational speed.

In the experimental setup for the hydrokinetic turbine model, different sensors and equipment were installed to measure and control various aspects of the system.

- TRS605 Rotational Force Sensor: This non-contact shaft-to-shaft rotary torque sensor, equipped with an encoder, was placed between the motor and propeller shafts. The reason is to precisely evaluate the driving torque applied to the system and to quantify the rotational speed of the turbine.

- ESCON 50/5 Servo Controller: This motor driver, known as an ESCON 50/5 servo controller, was used to maintain a setpoint motor rotational speed and control it to maintain a desired speed during testing.

- Current and Voltage Sensors: to measure the electrical power created by the hydrokinetic turbine, current sensors (ACS712) and voltage sensors (DC0-25V) were installed. These sensors allow us to screen the electrical current moving through the system and the voltage across the PMDC motor, which are fundamental for computing the generated power.

- Temperature and Humidity Sensors: for safety and performance monitoring, temperature and humidity sensors were installed. Two sensors type SHT30 and two DHT22 were utilized to measure the temperature and humidity levels inside the turbine nacelle.

The insert setup, which includes all these sensors and equipment, is shown in Fig. 5.1.
To process and analyze this data, a data acquisition system is employed. In this case, a National Instruments (NI) SCXI-1000 data acquisition system, integrated with LabVIEW software, is used. This system is capable of gathering analog signals from the various sensors. The data collected by these sensors is indispensable for understanding the presentation and conduct of the hydrokinetic turbine model during testing. By estimating force, rotational speed, electrical current, voltage, temperature, and humidity, we can obtain comprehensive information on the turbine's proficiency, power generated capabilities, and safety boundaries.

5.2. Testing Procedure
The testing procedure for understanding the hydrodynamic characteristics of the hydrokinetic turbine consists of several fundamental steps. Before conducting the experiments, the hydrokinetic turbine model is carefully positioned into the towing tank. It is situated appropriately relative to the towing arm, and the insert part containing the electro-machine and sensors is connected to the torpedo nacelle, ensuring a watertight seal. This step ensures that the turbine model is securely and accurately placed in the water for testing. Once the turbine model is submerged in the towing tank, it is towed or pulled through the water at a pre-selected speed while sensors installed on the model record data. These sensors measure crucial parameters such as torque, speed, and other relevant data during the towing process. This step is crucial as it provides valuable information on the turbine's performance under various flow conditions. The chose speed can be adjusted based on
the specific requirements of the test. After the towing process is complete, the data collected from the sensors is carefully interpreted. This analysis involves processing the sensor readings to determine various hydrodynamic characteristics of the turbine. Depending on the results obtained from the experimental tests and data analysis, further testing may be necessary to refine and improve the turbine's design. If certain aspects of the turbine's performance need enhancement or if specific conditions require additional evaluation, iterative testing allows us to make necessary adjustments to the turbine model and reiterate the testing process. Fig. 20 shows the prototype turbine submerged in towing tank.

Fig. 20. Photograph of the prototype turbine during the towing tank experiment.

To evaluate the hydrodynamic characteristics of the turbine, various fluid-related parameters are available in Table 4.1.

<table>
<thead>
<tr>
<th>Fluid Parameter</th>
<th>unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow Speed</td>
<td>m/s</td>
<td>0.05 – 1.95</td>
</tr>
<tr>
<td>Kinematic Viscosity</td>
<td>m²/s</td>
<td>1.0334 * 10⁻⁶</td>
</tr>
<tr>
<td>Dynamic Viscosity</td>
<td>kg/(m.s)</td>
<td>1.0318 * 10⁻³</td>
</tr>
<tr>
<td>Density</td>
<td>kg/m³</td>
<td>998.4</td>
</tr>
</tbody>
</table>
In addition, specifications of the propeller are given in Table 4.2.

Table 4.2. Blade specifications at towing tank operating condition.

<table>
<thead>
<tr>
<th>Blade Specifications</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor Diameter</td>
<td>25 cm</td>
</tr>
<tr>
<td>Number of the Blades</td>
<td>3</td>
</tr>
<tr>
<td>Airfoil</td>
<td>FX-77-W</td>
</tr>
<tr>
<td>Material</td>
<td>Stratasys ABS-Based Carbon Fiber Filament</td>
</tr>
</tbody>
</table>

Overall, this testing methodology is vital for gaining a comprehensive understanding of the hydrokinetic turbine's hydrodynamic characteristics.

5.3. Experimental Measurements

During the testing methodology of the hydrokinetic turbine model, the turbine is towed through the water at a picked speed. Different sensors are used to gather significant information during the towing system. These sensors incorporate current and voltage sensors, which measure the electrical power of the turbine, a torque sensor to measure the rotational force applied on the turbine, and temperature and humidity sensors for security monitoring. However, there is a restriction in the testing facility - the length limitation of the towing tank. Because of this restriction, the turbine might not have sufficient opportunity to arrive at the chosen steady state speed during the towing system. To conquer this restriction and ensure that the turbine works at the chosen speed for testing, a particular approach is employed. Before the carriage begins towing the turbine model, the PMDC motor, which serves as the prime mover, is initially powered to arrive at the steady state speed. Once the PMDC motor arrives at the steady state speed, the carriage begins towing the turbine model at the picked speed. During the towing process, the power utilized by the PMDC motor changes as it experiences the flow force of towing the turbine through the water. The distinction in power utilization by the PMDC motor between the underlying initial steady state operation and the towing stage addresses the unique energy given by the water flow. This dynamic energy is harnessed by the hydrokinetic turbine propeller and converted into rotational motor energy. Fig. 5.3. presents the PMDC motor's rotational speed measured at 500 rpm (revolutions per minute) at a towing speed of 6 feet per second (1.83 meters per second) as a function of time during the towing process. The graph shows that the rotational speed of the PMDC motor remains relatively constant and does not exhibit any major variations during the towing process. In other words, the line representing the rotational speed remains mostly flat, indicating that the motor's speed remains stable over time.
Fig. 5.3. Experimental measurements of the motor speed at the towing tank test.

Fig. 5.4. shows a graph of the electrical current waveform measured at a towing velocity of 6 feet each second (1.83 meters each second) as a function of time. During the towing process, as the hydrokinetic turbine model is pulled through the water at a speed of 6 ft/s, the motor current waveform displays explicit characteristics. One outstanding feature of the waveform is a drop in the motor current values during the towing process. The drop in the motor current values is a consequence of the dynamic energy provided by the water flow. As the water flows past the turbine propeller blades, it imparts energy to the turbine, causing it to rotate and generate power. This dynamic energy is harnessed by the hydrokinetic turbine and converted into rotational motor energy. As the turbine turns and produces power, the motor current waveform encounters changes. The variations in the motor current waveform directly correspond to the turbine's performance and power generation capabilities. While the motor rotational speed is constant, a lower motor current indicated that more power is being harnessed by the turbine propeller blades from water flow.
Fig. 5.4. Experimental measurements of the motor current at the towing tank test.

Fig. 5.5. presents a graph of the measured generated power at various carriage speeds during the experimental testing of the hydrokinetic turbine. The measurements were performed while towing the turbine model at various carriage speeds, ranging from 0 to 6.5 feet per second (0 to 1.98 meters per second). During the testing, the measurements were taken with the rotor propeller's rotational speed set at 500 rpm, and the input voltage approaching 12 volts. The voltage amplitude showed only a small fluctuation during the test. The graph indicates that the generated power by the hydrokinetic turbine varied with different carriage speeds. The maximum measured generated power achieved was 16.7 Watts, and this peak power output was observed when the turbine was towed at a velocity of 6.5 feet per second (1.98 meters per second). However, despite achieving a peak power output of 16.7 Watts, the turbine's overall performance was not optimal. The use of a planetary gearhead to achieve a slow driving mechanism in the ocean current turbine had some drawbacks. The gearhead, although effective in slowing down the turbine's rotational speed for its intended purpose, was not designed for use as a generator. As a result, the gearhead introduced inefficiencies, leading to poor efficiency in power generation. Despite the suboptimal performance, the experiment still exhibited a stable body disposition and output power. The turbine maintained a steady and consistent power generation performance during the tests.
Fig. 5.5. Experimental measurements of the generated power at the towing tank test.

The torque generated by the hydrokinetic turbine due to the flow of current is a critical factor as it directly influences the productivity and performance of the generator. If the torque is too low, the generator will not be able to deliver sufficient power, and the turbine may not operate effectively. On the other hand, if the torque is excessively high, it can potentially cause damage to the generator or the turbine itself. Therefore, it is essential to accurately measure and control the torque generated by the turbine to ensure both optimal performance and safety. Fig. 5.6. shows a graph that plots the measured generated torque as a function of the carriage speed during the experimental testing. The graph reveals that the amount of torque generated is directly proportional to the output power of the turbine. This means that as the power output of the turbine increases, the torque produced by the turbine likewise increases. As the turbine operates at higher power levels, it exerts more rotational force on its blades, resulting in an increase in the generated torque.
5.4. Comparison of Experiment and Mathematical Simulation

Fig. 5.7. illustrates how, when carriage speed is increased from 0 to 2 meters per second (m/s), the average generated power changes. The generated power is an indicator of the system's power output, which in an underwater current turbine transforms water kinetic energy into electrical energy. Plot findings from both the actual experiment and the blade element momentum (BEM) simulation demonstrate that when carriage speed increases, generated power also increases. This is as expected because the faster the fluid's speed, the more energy is available for the turbine blades to capture. The plot shows that for carriage speeds up to 1.8 m/s, the generated power derived from the BEM simulations was marginally less than the experimental results. This shows that the performance of the OCT may have been somewhat understated by the simulations. The generated power anticipated by the BEM calculations was, however, greater than the experimental findings until the carriage speed reached 2 m/s. These differences between the experimental data and the BEM simulations could be caused by a number of factors. One possibility is that there was some measurement error because the experimental setup or the equipment used to measure the generated power was not accurate enough. Another hypothesis is that some of the intricate
aerodynamic effects that manifest in actual OCT, particularly at higher water speeds, may not have been adequately represented by the BEM simulations.

Fig. 5.7. Generated power comparison.

Fig. 5.8. displays carriage speed on the x-axis and generated torque on the y-axis. The underwater current turbine blades' twisting force, known as "generated torque," moves the turbine's rotor, which ultimately produces electricity. The upward sloping trend in the graphic indicates that as the carriage speed is increased from 0 to 2 (m/s), the generated torque also increases from 0 to 0.3 (N.m) in the BEM simulation and 0 to 0.28 (N.m) in the experiment. This is to be expected because the quantity of energy available in the moving fluid, which rises with current speed, is directly proportional to the created torque. The experimental data showed that the torque was slightly less than what the BEM calculations had projected. This suggests that the performance of the underwater current turbine may have been somewhat overstated in the BEM simulations. The discrepancy was within a tolerable range of uncertainty, so the difference between the experimental data and the BEM simulations was not significant.
Fig. 5.8. Generated torque comparison.
6. Chapter 6: Repeated Dry Dynamometer Characterization with Magnetic Coupling

The primary objective of this revised dynamometer characterization testing is to determine the characteristic parameters of a PMDC motor configured for use as a small-scale experimental hydrokinetic turbine. Unlike the initial design, the dynamometer now incorporates a redesigned magnetic coupling to address previous issues related to leakage. The fundamental principle remains the same, with the PMDC motor serving as a prime mover connected shaft to shaft to an identical PMDC motor configured as a generator.

The dynamometer's behavior is governed by Kirchhoff's voltage law, considering identical armature resistors, armature inductances, angular speeds, and torques in both the power and load circuits. The power circuit equation is given by:

**Power circuit:**

\[ E_a = R_a i_a(t) + L_a \frac{d i_a(t)}{dt} + K_e \omega(t) \]  \hspace{1cm} (6.1)

**Load circuit:**

\[ E_b = R_a i_b(t) + L_a \frac{d i_b(t)}{dt} + R i_b(t) \]  \hspace{1cm} (6.2)

where \( R \) is the variable resistor [Ω] and \( i_b \) is the generated current [A].

In the case of a constant operating point, equations (6.1) and (6.2) can be simplified as follows:

**Power circuit:**

\[ E_a = R_a i_a + K_e \omega \]  \hspace{1cm} (6.3)

**Load circuit:**

\[ K_e \omega = (R_a + R) i_b \]  \hspace{1cm} (6.4)

6.1. Revised Experimental Setup

To enhance accuracy, a specific experimental setup is employed, incorporating two identical PMDC motors. The connection of PMDC motors, a variable DC voltage source, gearhead for speed adjustment, rotary torque sensor, and a servo motor driver is maintained from the initial design. The key modification is the introduction of a redesigned magnetic coupling to address leakage issues and enhance system reliability.
This setup ensures precise control over the prime mover's speed and allows for comprehensive data collection on torque, speed, and electrical characteristics.

6.2. Impact of Magnetic Coupling
The introduction of the magnetic coupling into the system has a subtle impact on the overall performance. One notable effect is a slight reduction in the rotational speed when compared to both the initial dry test and the numerical results as shown in Fig. 6.2.
Fig. 6.2. Revised prime mover voltage-motor speed plot.
Fig. 6.3. Revised generated current plot.
The incorporation of the magnetic coupling into the system has led to a marginal decrease in both the generated current (Fig. 6.3) and generated torque (Fig. 6.4) in comparison to the initial dry test. This outcome aligns with expectations, considering the observed reduction in rotational speed.

The introduction of a magnetic coupling in the system, while resulting in a minor reduction in overall performance, is deemed essential due to its pivotal role in preventing shaft leakage—a critical issue faced in the initial design. The compromise in performance, evidenced by a slight decrease in rotational speed, generated current, and torque, serves as a trade-off for the enhanced system integrity achieved through the magnetic coupling's ability to seal the shaft. In marine applications, where exposure to corrosive elements is a significant concern, the magnetic coupling proves invaluable by providing a hermetic seal without the need for traditional seals susceptible to wear and corrosion. The technology's benefits include reduced maintenance, enhanced reliability, and resistance to corrosion, positioning magnetic couplings as crucial components in marine systems, aligning with the imperative for robust and durable solutions in challenging environments.

Fig. 6.4. Revised driving torque plot.
7. Chapter 7: Nacelle Redesign and Construction

During the first experiment run, a leakage issue was identified occurring from the propeller pipe. This indicates that water was escaping from the area around the propeller, which is a concern as it can affect the experiment's integrity and the functionality of the turbine for the further research. To address the leakage issue, a solution involving a magnetic coupling through the shaft was implemented. A magnetic coupling is a mechanism that allows the transfer of torque between two rotating shafts without direct physical contact. It is often used in situations where a water-tight seal is needed, as it prevents fluid leakage.

The next step involved redesigning the nacelle, specifically the torpedo component, to accommodate this solution and ensure water-tightness. This redesign included dividing the torpedo nacelle into two distinct segments:

- Wet Department: This segment houses the components that are exposed to water, including the propeller and the magnetic coupling mechanism.
- Dry Department: This segment is designed to remain dry and houses components that should not be exposed to water, such as electrical components or sensors.
- Wall Installation: A key feature of this redesign is the installation of a wall between the wet and dry departments of the torpedo nacelle. The magnetic coupling is placed within this wall, between the wet and dry departments. This positioning allows the magnetic coupling to function effectively while preventing any water from entering the dry department.

The wall acts as a barrier, effectively sealing off the wet department from the dry department. It ensures that any leakage from the propeller pipe is contained within the wet department and does not affect the dry components.

7.1. Redesign in Solidworks
The redesign was specifically implemented in the front piece of the torpedo nacelle. This piece was split into two parts, and the wall was inserted between them to create the separation between the wet and dry departments.
Fig. 7.1. Solidworks sketch of the wet part of the torpedo.

Fig. 7.2. Solidworks sketch of the wall barrier of the front piece of nacelle.
The modification involved the use of a magnetic coupling and the redesign of the torpedo nacelle to prevent water leakage from the propeller pipe. The installation of a wall between the wet and dry departments, particularly in the front piece of the torpedo, ensures that the magnetic coupling can function as intended while maintaining a water-tight seal, enhancing the overall integrity of the experiment and data collection process.

7.2. Print and Assembly
To new components of the torpedo nacelle design were reprinted using PETG filament. A new 3d printer was utilized using for this task. This printer offered improved printing capabilities allowing you to create the necessary components for your redesigned nacelle.

![Fig. 7.3. 3D printer.](image)

After the 3D printing process was completed, the same post-printing work in the UNO (University of New Orleans) model shop were conducted. This is a crucial step to prepare the printed components for assembly and testing.
The printed components included support structures that need to be removed. Careful removal of support material is essential to avoid damaging the structural integrity of the printed pieces. To ensure a smooth and uniform surface finish, the printed pieces were sanded. This step enhances the aesthetics of the components and may also improve their hydrodynamic performance.
Fig. 7.5. Sanding the torpedo pieces.

The printed components, except for the rear cap, were assembled. The rear cap serves to close the access point for the insert. Additionally, the front piece, which represents the wet department, was
prepared for attachment to the rest of the nacelle (dry department). These components were secured in place using appropriate screw.

Fig. 7.6. Gluing the torpedo pieces.

To further enhance water-tightness and prevent leakage, the entire model was coated with epoxy. Epoxy is a strong adhesive and sealant known for its waterproofing properties. The epoxy coating provides an additional layer of protection against water ingress.
The insert that was previously used in the first run of experiments was reused due to the fact that the insert performed its intended function effectively, and there was no need for replacement.
Fig. 7.8. Insert slides within the torpedo nacelle.

The wet compartment within the torpedo structure that explicitly designed to house the second pair of the magnetic coupling is shown in below.
Fig. 7.9. The wet compartment.

To ensure water-tightness around the pipe and turbine, the same type of wax for sealing was used. By applying wax, the pipe and turbine connections were secured.
The same method maintained to attach the turbine to the towing tank carriage. This consistency ensures that the turbine remains securely fastened during testing, just as it was in the initial run.
The same data acquisition system that was employed in the first run of experiments was used again for the second run. This ensures consistency in data collection methods, allowing for direct comparisons between the results obtained in both runs. The safety system, which includes monitoring temperature and humidity and activating an alarm if unusual readings are detected, remained unchanged for the second run. Consistency in safety measures is essential to protect the equipment and ensure the safety of personnel.
As in the first run, an initial test was conducted before submerging the turbine into the tank. This step serves as a final check to verify that all components are functioning correctly and that the setup is ready for the actual experiment.
The same sequence of actions as described in the first run were followed. This systematic approach ensures that the conditions and procedures of the initial experiment was replicated, enabling us to compare the results and assess any changes or improvements made between the runs.
8. Chapter 8: Repeated Test Procedure

8.1. Data acquisition systems and instruments setup

For this round of testing, we adhered to the same instrumentation utilized in our previous trials, with a notable alteration in the coupling mechanism. The hydrokinetic turbine model integrates an electric motor capable of functioning as a generator, accompanied by an array of sensors, all housed within the insert. Specifically, we employed a PMDC motor of the DCX 35 L type, boasting a power rating ranging from 80 to 120 Watts, as the motor/generator. To exert precise control over its operation, the PMDC motor was linked to a driver, facilitating regulation of the motor's speed. A variable DC voltage source, connected to the driver, was employed to adjust the motor speed by varying the input voltage. The motor, with a speed rating of 8130 RPM, was paired with a planetary gearhead (GPX 37) featuring a reduction ratio of 16:1 to accommodate the scaled-down size of the turbine model. This gearhead choice was imperative due to the model's constraint on rotational speed. In the experimental setup, consistent with our prior work, a range of sensors and equipment was integrated to measure and control various parameters of the hydrokinetic turbine system. Notable instruments included the TRS605 Rotational Force Sensor, serving to precisely gauge driving torque and turbine rotational speed. The ESCON 50/5 Servo Controller, a motor driver, maintained a setpoint rotational speed and adjusted it as required during testing. Current sensors (ACS712) and voltage sensors (DC0-25V) were employed to measure electrical power generation, crucial for computing the generated power. Additionally, temperature and humidity sensors, consisting of SHT30 and DHT22 types, were strategically placed for safety and performance monitoring within the turbine nacelle. Despite maintaining the consistency of the overall instrumentation from our previous testing, the magnetic coupling replaced the Spyder coupling in the current setup. The integrated sensors and equipment are visually represented in Figure 8.1.

Fig. 8.1. Electrical instruments setup.
8.2. Towing tank carriage setup
The evaluation of hydrodynamic characteristics for the hydrokinetic turbine involved a systematic process closely mirroring our prior testing methodology. Before initiating experiments, precise positioning of the turbine model within the towing tank ensured optimal alignment and a watertight seal. Subsequently, the turbine underwent towing at a predetermined speed, capturing vital data through installed sensors measuring torque and speed. This approach provided valuable insights into the turbine's performance under varying flow conditions. Notably, the methodology employed in this testing phase, featuring a magnetic coupling, replicated the exact procedure utilized in previous tests. Emphasizing continuity, we maintained identical numerical values to ensure a meticulous repetition of our prior experiments. Fig. 8.2. visually illustrates the prototype turbine submerged in the towing tank, showcasing the consistent application of our established testing protocol.

Fig. 8.2. Photograph of the redesigned prototype turbine during the towing tank experiment.
8.3. Results and Discussion
In our redesign nacelle experiments utilizing a magnetic coupling, we maintained an identical protocol to the one used in our previous testing. The comparison of generated power and torque involved plotting data from three distinct methods on a single graph. The solid line represents the numerical method utilizing blade element momentum (BEM) theory, the black squares denote our prior testing without a magnetic coupling, and the red stars signify measurements obtained with the magnetic coupling. Examining the plotted findings, both from the actual experiments and the BEM algorithm, reveals a consistent trend: as the carriage speed increases, the generated power also experiences an increment. This alignment with expectations stems from the principle that a faster fluid speed provides more energy for the turbine blades to capture. Up to a carriage speed of 1.8 m/s, the generated power from BEM simulations was marginally lower than the experimental results, suggesting a potential understatement of the Ocean Current Turbine (OCT) performance by the simulations. However, beyond 2 m/s, the BEM-calculated generated power surpassed the experimental findings. Discrepancies between experimental data and BEM simulations may arise from measurement inaccuracies in the experimental setup or equipment, or the intricate aerodynamic effects in actual OCT, especially at higher water speeds, inadequately represented by BEM simulations. Furthermore, measurements with the magnetic coupling exhibited slightly lower values than prior experimental measurements, attributed to the discussed impact of the coupling on the system.

![Fig. 8.3. Generated power comparison.](image-url)
In conclusion, this study represents a significant advance in the development and evaluation of a compact horizontal axial ocean current turbine (OCT) using Blade Element Momentum (BEM) simulations. The integration of a sophisticated mathematical model adapted to the design of the propeller blades enables a precise calculation of the hydrokinetic loads, showing a comprehensive understanding of the behavior of the turbine. An innovative combination of simulation and experiment and marine-inspired dynamometer testing contribute to standardized empirical evaluation and valuable knowledge of turbine performance. An experimental setup of a 3D printed turbine model equipped with sensors facilitates monitoring the relationships between power, force and rotational speed generated by a permanent magnet motor (PMDC) during towing tank tests. Comparisons with BEM simulations highlight the robustness of the model and show close agreement with some variants. Factors such as measurement accuracy and aerodynamic effects contribute to these variations, emphasizing the importance of a comprehensive approach that combines simulation and experiment.

In particular, the study successfully addressed previous small leakage problems by redesigning the machine and introducing magnetic coupling. This strategic redesign not only helps challenges, but also allows for longer-term, leak-free testing. This improvement greatly contributes to our understanding of the performance of small-scale ocean current turbines at different speeds. The interdisciplinary nature of this research, which combines mathematical modeling, experimental
testing and innovative design solutions, promises further development in the field of hydrokinetic energy conversion.
Conclusions

Contextualizing the Shift Towards Hydrokinetic Energy:

The dissertation addresses a critical need in the contemporary energy landscape, marked by an escalating demand for sustainable alternatives to conventional fossil fuels. Environmental concerns related to petroleum derivatives have prompted a profound reevaluation of existing energy sources. Hydrokinetic energy, derived from the kinetic movement of water bodies, emerges as a viable and underexplored solution. The dissertation recognizes the urgency for innovative methodologies to effectively utilize and harness this energy, particularly focusing on horizontal-axis turbines.

Distinctive Performance Characteristics of Horizontal-Axis Turbines:

The exploration of various turbine configurations underscores the distinctive performance characteristics of horizontal-axis turbines in converting the dynamic energy of water currents. The adaptation of a conventional horizontal-axis wind turbine for water currents represents a groundbreaking achievement. This adaptation, supported by experimental and computational methodologies, leverages water's unique properties and insights derived from computational fluid dynamics (CFD) analysis, showcasing enhanced performance.

Empirical Validation for Optimizing Hydrokinetic Turbines:

Aligning with the trajectory of wind turbine development, the dissertation emphasizes the necessity for empirical validation through systematic experimentation to comprehensively understand and optimize hydrokinetic turbine behavior. The testing approach utilizing towing tanks mirrors established methodologies in wind energy, highlighting the commonality with horizontal-axis turbines. Specialized numerical methods, validated through a simulation tool based on Blade Element Momentum (BEM) theory, instill confidence in their applicability for marine current turbine development.

Pioneering Dynamometer Testing Methodology:

The central focus on dynamometer testing of hydrokinetic turbines introduces a pioneering methodology employing towing tanks as a testing platform. The integration of a minimized hydrokinetic turbine model within a 3D-printed watertight nacelle, equipped with sensors, facilitates comprehensive data collection. This approach not only quantifies energy consumption but also extracts crucial hydrodynamic characteristics, including torque and power generation. This groundbreaking method marks a promising avenue for standardized testing procedures, enhancing the reliability and repeatability of hydrokinetic turbine assessments.

Addressing Market Opportunities and Adherence to ITTC Guidelines:

The dissertation expands its reach to the potential market opportunities derived from harnessing hydrokinetic energy. By aligning with well-established methods in the wind energy sector and adhering to guidelines set by the International Towing Tank Conference (ITTC), the proposed
methodology covers a spectrum of crucial aspects. These encompass adaptation of towing tanks, scale model selection, instrumentation, dry dynamometer characterization, nacelle design, testing procedures, and redesign with magnetic coupling. This comprehensive approach positions the dissertation's findings within the broader context of industry standards and market readiness.

The Revolutionary Impact and Future Contributions:

In essence, the dissertation seeks to revolutionize underwater turbine testing by amalgamating principles from naval architecture with the unique challenges of hydrokinetic energy. The proposed methodology ensures robustness, repeatability, and valuable insights into the hydrodynamic performance of hydrokinetic turbines. By advancing the field of ocean current energy conversion technologies, this study contributes significantly to the global pursuit of renewable energy sources. The findings pave the way for sustainable and efficient underwater energy solutions, marking a transformative impact on the future of hydrokinetic energy.
References


[101] https://www.uno.edu/academics/coe/name/facilities/towing-tank

[102] ITTC Recommended and Guidelines, Open Water.

[103] https://www.ittc.info/media/8025/75-02-03-021.pdf


[108] https://www1.eere.energy.gov/hydrogenandfuelcells/tech_validation/pdfs/fcm01r0.pdf


[113] Sofoklis S. Makridis, Hydrogen Storage and Compression, Chapter 1, CH001 18 June 2016; 11:30:20


[116] Bulk hydrogen storage, Presentation at the Strategic Directions for Hydrogen Delivery Workshop, Crystal City, USA, May 7-8, 2003.


[120] COMSOL’s CFD Module User’s Guide (Version 5.4)
[123] https://h2tools.org/hyarc/hydrogen-properties,
[124] http://homepages.wmich.edu/~cho/ME432/Appendix1Updated_metric.pdf,
[133] http://hyperphysics.phyastr.gsu.edu/hbase/Kinetic/shegas.html
Mahdi Deymi-Dashtebayaz, Mahmood Farzaneh-Gord, Hamid Reza Rahbari, “Simultaneous Thermodynamic Simulation of CNG Filling Process”. Polish Journal of Chemical Technology, 16, 1, 7—PolJCh, 1C0h.2e4m78. /Tpejcht-·2,0V1o4l-.01060,.2.
William E. Liss, Mark Richards, Kenneth Kountz, Kenneth Kriha, “Development and Validation testing of Hydrogen fast-fill fueling algorithms”.
Vasileios Tzelepis, Electromechanics of an Ocean Current Turbine, University of New Orleans Theses and Dissertations, 2015.
mmag, Urs Kafader, Maxon motors as generators, Maxon Academy, Revision 2019.
Nikolaos I. Xiros, et al. Theoretical and experimental investigation of unmanned boat electric propulsion system with PMDC motor and water jet.
Abraham Pressman, Switching power supply, Second edition.
S. K. Sahdev, Electrical Machines, Cambridge University Press.


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