CORRECTION OF SHIPS' STEERING ANGLE FOR SAFE MANEUVERING AGAINST STRONG WINDS USING MICROCONTROLLER

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MSc/PG Diploma in Industrial Automation

Department of Electrical Engineering

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Dissertation submitted in partial fulfillment of the requirements for the degree
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DECLARATION

I declare that this is my own work and this Dissertation does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or Institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text. I retain the right to use this content in whole or part in future works (such as articles or books).

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The above candidate has carried out research for the MSc/PG Diploma in Industrial Automation Dissertation under my supervision. I confirm that the declaration made above by the student is true and correct.

Name of Supervisor: Dr. RM Maheshi Ruwanthika

Signature of the Supervisor: Date: 13 June 2025

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ABSTRACT

The maritime industry, responsible for approximately 80% of global trade volume, faces significant challenges posed by adverse weather conditions, particularly strong winds. Over-steering in such conditions increases the risk of capsizing, leading to substantial economic and human losses. This research presents the development of a microcontroller-based system designed to adjust ship steering angles in real-time, accounting for wind conditions and enhancing navigational safety. The system integrates various sensors, including wind speed and direction transducers, gyro modules, and GPS receivers, to continuously monitor both environmental conditions and navigational parameters. Data collected from these sensors are processed by a microcontroller, which utilizes a developed mathematical model to assess the impact of wind forces on the ship's motion. Based on this assessment, the model calculates the necessary steering angle adjustments to counteract the effects of wind forces, ensuring stable and safe maneuvering. Key factors considered in the model include wind force, centrifugal force, and heel angle, providing a comprehensive evaluation of ship stability under varying wind conditions. The system is designed to be compatible with existing steering mechanisms, ensuring cost-effectiveness and ease of implementation. Simulations demonstrate the system's ability to predict and correct steering angles accurately, significantly reducing the risk of over-steering and capsizing. Rigorous testing has validated the system's performance, showing substantial improvements in navigational safety under strong wind conditions. The proposed solution offers a robust method for enhancing maritime safety, protecting both crew and cargo.

Keywords: Microcontroller, Maritime, Steering angle, Mathematical models

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LIST OF ABBREVIATIONS

Abbreviation	**Description**
ADC	Analog-to-Digital Converter
AIS	Automatic Identification Systems
AVR	Advanced Virtual RISC
AVS	angle of vanishing stability
CAN	Controller Area Network
CFD	Computational Fluid Dynamics
CMU	Central Microcontroller Unit
CPU	central processing unit
EEPROM	Electrically Erasable Programmable Read-Only Memory
GPS	Global Positioning System
HMI	Human-Machine Interface
HVAC	heating, ventilation, and air conditioning
LNG	liquefied natural gas
LPG	liquefied petroleum gas
MEMS	Micro-Electro-Mechanical Systems
MWV	Marine Wind Velocity
NMEA	National Marine Electronics Association
ROT	Rate of Turn
SMA	shape memory alloy
SOG	Speed Over Ground
SRAM	Static Random Access Memory
UI	User Interface

CHAPTER 1

INTRODUCTION

Maritime navigation is the backbone of global trade as approximately 80% of the global trade volume transported by sea [1]. The ships offer a wide range of cargo capacities and are capable of handling a wide range of products from raw materials to various types of products. Further naval ships/crafts are involved to protect their countries from external treats come through the sea.

However, the safety and efficiency of maritime operations are often compromised by adverse weather conditions, particularly strong winds. These conditions pose significant challenges, including the risk of over-steering, which can lead to capsizing and substantial economic and human losses. Each year, more than 20 major vessels sink due to mechanical failures, human error, and inadequate safety precautions in rough seas [2].

1.1 Background

Industry is crucial to the international economy, ensuring the movement of goods and commodities across vast distances. Compared to other modes of transportations such as air freight and land transportation, shipping offers more cost - effective solutions [3]. Figure 1.1 represents seven categories of ships that involved in transporting goods across the world.

1. **Container Ships:** Container ships are large, specialized vessels designed to transport cargo in standardized containers. These ships are the backbone of global trade, enabling the efficient and cost-effective transportation of goods across oceans. Key features of container ships are specialized design, capacity, and efficiency. Container ships are essential for the modern supply chain, carrying goods such as electronics, machinery, food, and textiles across the globe. Their standardized approach to cargo handling has revolutionized the shipping industry, making it faster and more economical [4].
2. **General Cargo Ships:** General cargo ships are versatile vessels designed to transport a wide variety of goods that cannot be shipped in standardized containers. These ships are equipped to handle various types of cargo, including packaged goods, machinery, timber, and bulk commodities like grain or steel. Key features of general cargo ships include flexibility, cargo handling equipment, and size range. General cargo ships play a crucial role in transporting goods that require specialized handling or are shipped in smaller quantities. They are

essential for trade in regions with limited containerized shipping infrastructure or for delivering oversized and irregularly shaped items [5].

3. **Tankers:** Tankers are specialized vessels designed for the bulk transportation of liquids and gases, such as crude oil, refined petroleum products, chemicals, liquefied natural gas (LNG) , and edible oils. These ships are critical to global trade, ensuring the efficient movement of essential commodities across oceans. There are different types of tankers such as oil tankers, chemical tankers, and LNG or liquefied petroleum gas (LPG) tankers. Safety systems and size range are key features of tankers. Tankers are essential for energy transportation, enabling the global supply of fuel and other liquid commodities. With their sophisticated design and operational safety measures, they remain a cornerstone of the shipping industry [6].

4. **Dry Bulk Carrier:** Dry bulk carriers are specialized ships designed to transport unpackaged bulk cargo in large quantities. These cargoes include dry goods such as grains, coal, iron ore, cement, and fertilizers. Dry bulk carriers play a critical role in global trade, moving raw materials efficiently across oceans. Key features of dry bulk carriers are design and self-loading/unloading. There are different types of dry bulk carriers: Handysize (smaller carriers), Panamax (designed to fit through the Panama Canal), Capesize (large carriers), Supramax and Ultramax (medium-sized vessels). Dry bulk carriers are essential for transporting raw materials for industries such as steelmaking, power generation, and agriculture. They are optimized for efficiency and economy, ensuring the timely and cost-effective movement of large volumes of cargo [7].

5. **Multi – purpose Vessels:** Multi-purpose vessels are versatile ships designed to handle a wide range of cargo types, including general cargo, bulk cargo, and containerized goods. They are highly adaptable, making them ideal for routes with diverse cargo demands or ports with limited infrastructure. Key features of Multi-Purpose Vessels are cargo flexibility, onboard equipment, compartments, and size range. Multi-purpose vessels are commonly used in trade routes requiring flexible cargo handling solutions. They are ideal for transporting project cargo, such as wind turbine components, as well as serving regions with limited infrastructure where containerized shipping may not be feasible [8].

6. **Reefer Ship:** Reefer ships are specialized vessels designed to transport perishable goods that require temperature-controlled environments, such as fruits, vegetables, meat, seafood, dairy products, and pharmaceuticals. These ships are essential for maintaining the cold chain during long-distance transportation, ensuring the quality and freshness of sensitive cargo. Key features of Reefer ships

are temperature control, insulated cargo holds, cargo handling, and hybrid functionality. Reefer ships are widely used in global trade for transporting perishable goods across continents, serving industries such as agriculture, food processing, and pharmaceuticals. They play a critical role in maintaining supply chains and ensuring food security worldwide [9].

7. **Roll On/ Roll Off vessels:** Roll-on/Roll-of vessels are specialized ships designed to carry wheeled cargo, such as cars, trucks, trailers, and other vehicles, that can be driven on and off the vessel via ramps. These ships provide efficient and secure transportation for vehicles, making them vital for the automotive industry and other sectors reliant on wheeled transport. Key features of roll-on/roll-of vessels are vehicle decks, loading mechanism, cargo types, ventilation systems, and size variants. Roll-on/Roll-of vessels are widely used in international trade to transport vehicles and machinery efficiently. They also serve domestic routes as ferries, providing reliable and frequent transportation for cars and passengers between ports [10].

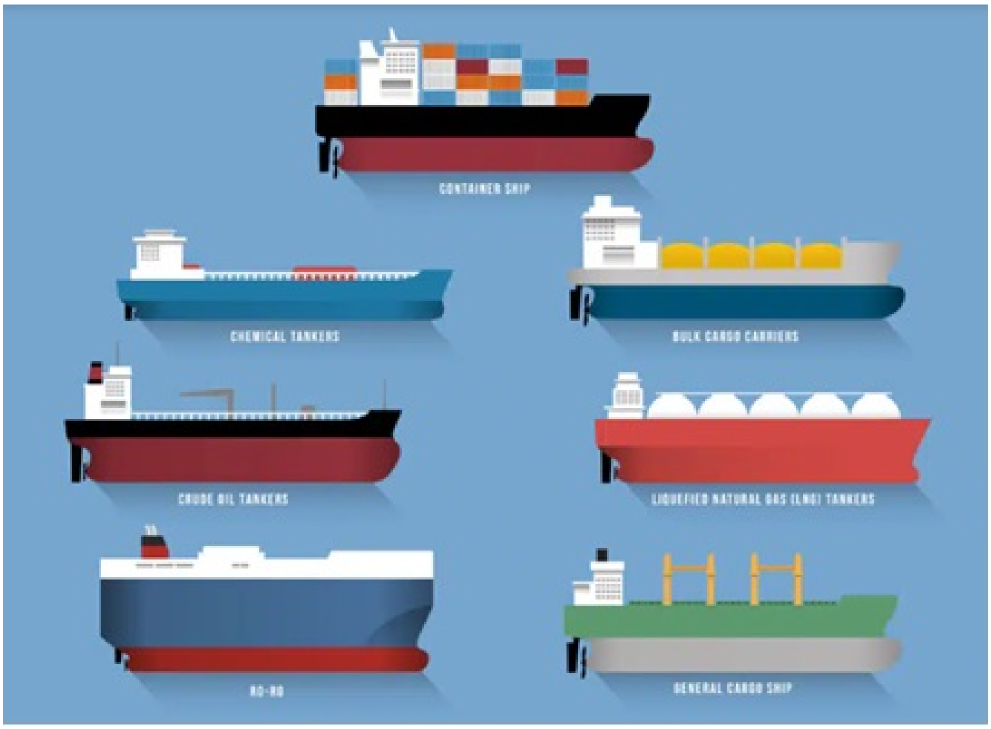


Figure 1.1: Types of ships

The safe and efficient journey of a ship is primarily based on the skills, judgment, and strategic decisions of its navigator. This pivotal role requires the navigator to utilize their extensive knowledge and expertise to chart an optimal course that ensures both safety and efficiency. They must accurately determine the current position of the vessel using advanced navigation tools and techniques, while continuously forecasting potential challenges, such as weather conditions, ocean currents, and obstacles. Additionally, the navigator plays a critical role in maintaining harmony with maritime traffic by carefully coordinating the ship's movements with those of other vessels, adhering to international regulations, and ensuring smooth and collision-free navigation in shared waterways [11].

Operation of ships at sea is not easy, and various human and mechanical factors are involved for safe voyage at sea. Figure 1.2 shows number of ship losses worldwide from 2013 to 2022. Among more than 100 gross tonnage ($100GT$) ships, total twenty-six of major vessels were counted as losses in year 2023 due to mechanical failures, human error, and insufficient safety precautions in rough seas. Among these twenty-six major vessel sunk incidents, sixteen were cargo ships related causing, significant impact to the global goods transportations [12]. In addition to marine accidents, more than 7000 tons of oil spills have been reported in the past 56 years, causing severe damage to the marine environment [13].

Sea conditions, including wind strength, wind patterns, wave dynamics, and ocean currents, are known to vary significantly over time and across different geographical locations. These fluctuations introduce considerable uncertainty, which poses challenges to effective navigation. The unpredictability of marine conditions can heavily impact a vessel's operations, as varying sea states may impose restrictions on maneuverability, speed, and overall efficiency. Navigators must adapt to these dynamic conditions to ensure safe and efficient passage, requiring a combination of expertise, real-time data, and strategic decision-making [14].

The safety and efficiency of maritime operations are often compromised by adverse weather conditions, particularly strong winds [15, 16]. These conditions pose significant challenges, including the risk of over-steering with strong wind condition, which can lead to capsizing and substantial economic and human losses.

Maritime navigation becomes increasingly complex due to the ever-changing and unpredictable marine environment. Among the various challenges, strong winds significantly impact a ship's stability and maneuverability, often pushing conventional steering systems beyond their limits. These systems frequently struggle to compensate effectively under such conditions, leading to over-steering. Over-steering occurs when the rudder is turned too aggressively, causing the vessel to tilt excessively and elevating the risk of capsizing. This issue not only jeopardizes the safety of the crew and cargo but also introduces considerable financial losses and potential environmental hazards. The study of maritime safety and navigation has a long and rich history, with extensive research focused on understanding and reducing risks associated with adverse weather conditions. One foundational text in this field, "Ship Stability for Masters and Mates" by Derrett and Barrass, offers comprehensive insights into the principles of ship stability and the factors influencing it. The book highlights the critical importance of

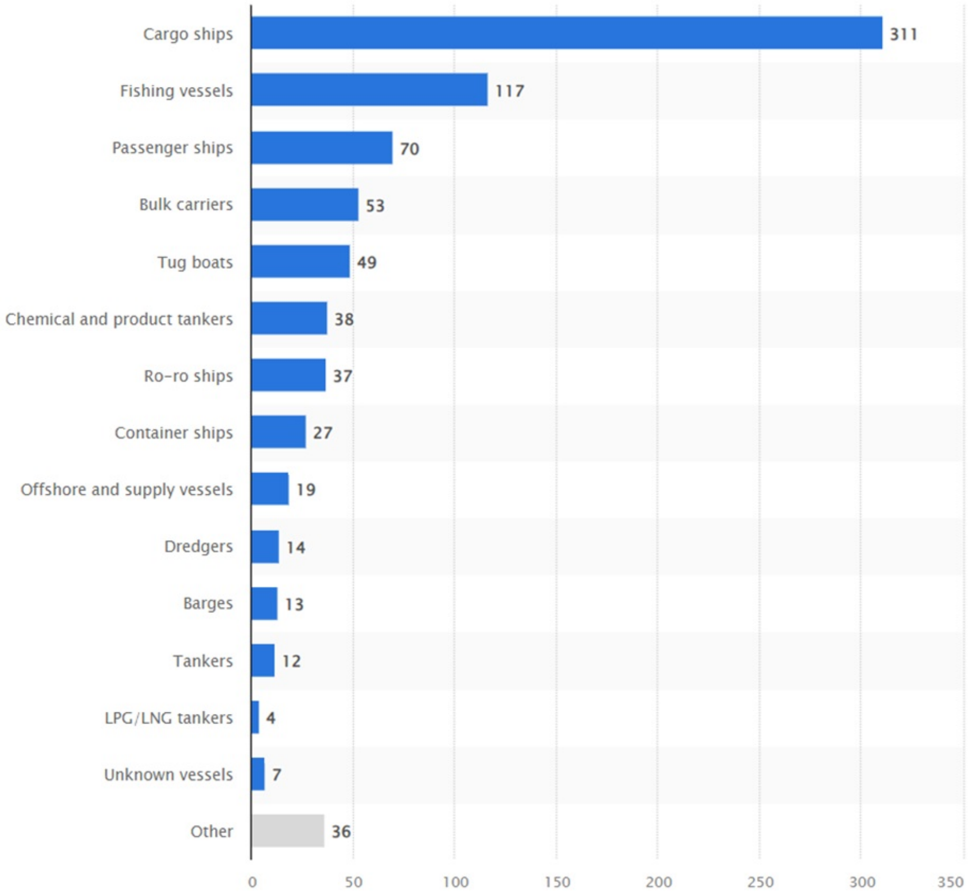


Figure 1.2: Number of ship losses worldwide from 2013 to 2022

maintaining a ship's stability under various conditions, including strong winds [17].

In the exploration of ship motion control, Ostretsov Genrikh Ehrazmovich, Beloaortseva Marina Viktorovna, and Kliachko Lev Mikhailovich [18] identified techniques for managing a ship's motion to address stability issues and mitigate the impact of wind on vessels. However, this research does not delve into strategies for reducing the threat of capsizing caused by strong winds.

A more detailed analysis, "Predicting the Wind Load Direction to Naval Vessels Resistance," investigates how wind affects ship stability. The study employs Computational Fluid Dynamics (CFD) simulations to evaluate the effects of wind direction on vessel resistance in calm water conditions, providing accurate predictions for optimizing resistance [19]. These findings support navigators in making informed decisions while sailing and aid ship designers in arranging equipment and optimizing resistance to wind impact. Despite these contributions, the study does not address specific strategies for mitigating wind effects on moving ships.

Marek Szymonski examines the impact of wind resistance on ships underway, particularly during harbor maneuvers or navigation in restricted waterways in his study of "Some Effects of Ships' Maneuverability". The research highlights that wind resistance is proportional to the square of relative wind speed, wind direction, and the ship's projected windage area. It describes the effect of wind pressure on the ship's superstructure and housing, emphasizing how large windage areas can adversely affect maneuverability. This information is among the recommendations for inclusion in a ship's maneuvering booklet, as per IMO Resolution A.601(15) [20]. However, the study does not explore approaches to mitigate wind pressure on ships while in motion.

1.2 Problem Statement

The key word for navigation is accuracy. Navigators must utilize their expertise, knowledge, and competence to plan precise routes, determine the ship's exact position, anticipate potential challenges, and coordinate the vessel's movements with neighboring ships operating along their own paths.

Numerous studies have been conducted to explore safe ship maneuvering at sea [21–25]. However, gaps remain in addressing navigation safety in strong wind conditions. This highlights significant opportunities within the shipping industry to enhance vessel safety against environmental factors.

A review of past research on the risks faced by ships in strong wind conditions reveals a lack of clear guidelines or precise methods to mitigate the impact of wind on a ship's superstructure. This knowledge gap significantly affects safe ship handling at sea, increasing the risk of capsizing when steering under strong wind conditions.

Modern ships are equipped with various sensors designed to collect environmental data critical for ensuring a safe and smooth voyage [26]. These sensors provide real-time information on weather conditions, humidity, water temperature, wind speed, wind direction, and more. While onboard systems have been integrated with these sensors to facilitate smoother operations, current technology lacks any sensor-based system to detect and address wind pressure on a ship's superstructure.

Despite advancements, there is still no effective mechanism to prevent over-steering in strong wind conditions. This deficiency poses a significant risk of capsizing and cargo loss. The absence of such a solution underscores the need for an innovative approach that integrates real-time environmental data with a ship's steering systems to enhance maritime safety.

1.3 Aims and Objectives

Navigating safely in strong wind conditions presents a persistent challenge in the maritime industry, posing risks to vessel stability, cargo safety, and environmental security. To address these challenges, this project focuses on developing an integrated system that leverages advanced technologies and mathematical modeling to enhance maritime safety.

The primary aim of this research is developing a microcontroller-based ship's motion control system that can correct ships' steering angles in response to real-time wind conditions, thereby enhancing navigational safety and preventing over-steering in strong wind condition by protecting ship from capsizing or its cargo losses.

The objectives outlined in this section aim to design a robust sensor system for real-time environmental data collection, formulate a mathematical model to assess and mitigate wind-induced forces, and implement a steering correction system to ensure safe vessel operation under adverse conditions. These objectives collectively contribute to creating an innovative solution that addresses the critical issue of over-steering in strong wind scenarios.

1. **Design a Sensor System:** Ships are equipped with various type of sensors to collect environmental parameters and ships data. With the help of that sensor systems, it is required to develop a comprehensive sensor system capable of measuring real-time wind speed, wind direction, and navigation data. This comprehensive sensor system will collect the essential navigational and environmental data inputs which required to develop a comprehensive mathematical model to prevent over steering of the ship in strong wind condition.

2. **Create a Mathematical Model:** Formulate a mathematical model to determine the wind force applied to the ship superstructure. According to that wind force, mathematical model will be further developed to derive ship's steering angle correction against the strong wind condition. This developed mathematical model will be incorporated with the key factors such as wind force, circular motion force, and heel angle to provide a comprehensive assessment of the ship's stability under varying wind conditions.

3. **Develop a Steering Correction System:** Integrate the developed sensor system and mathematical model with the ship's existing steering mechanisms. This integration aims to ensure that operation of the rudder of the ship whitens the safe range with providing a practical solution for the risk face by maritime industry.

CHAPTER 2

SYSTEM DEVELOPMENT

Developing the mechanism with the help of a comprehensive sensor integration system and a mathematical model based on that system needs to be integrated with the ship's existing steering gear mechanism of the ship. To understand the implementation process, it is essential to have a clear understanding of the steering gear mechanism on board ships.

2.1 Stearing Gear System

The steering gear system facilitates the movement of the rudder in response to a signal originating from the bridge or any other control point on the ship equipped to manage the rudder [27]. Figure 2.1 represents main components of the steering gear system. This system primarily consists of three major components [28]:

1. **Control Equipment:** The control equipment of a steering gear system is critical for the safe and efficient operation of a ship's steering mechanism. This equipment is designed to enable the operator to control the rudder, which in turn dictates the direction of travel of the ship. Steering gear systems can be manually or electronically controlled, and modern systems often feature automated control and redundancy for increased reliability.

2. **Power Unit:** The Power Unit of a steering gear system is a critical component responsible for generating the force necessary to move the rudder and steer the ship. The power unit converts energy into mechanical motion, typically using hydraulic or electric systems, to energize the ship's direction control system.

3. **Transmission Unit to the Rudder Stock:** The transmission system, or steering gear, enables the rudder's movement by converting and applying the transmitted control force.

The turning control force is initiated at the wheel at the helm. This force is transmitted to the steering system, which generates a torsional force on a specific scale. This torsional force is then applied to the steering gear, ultimately rotating the rudder to achieve the desired directional change.

There are three types of steering gear systems:

1. **Hydraulic Steering Gear:** The hydraulic steering gear is a widely used system on ships to adjust and maintain the rudder position to control the ship's direction. It operates by converting hydraulic energy into mechanical force to move

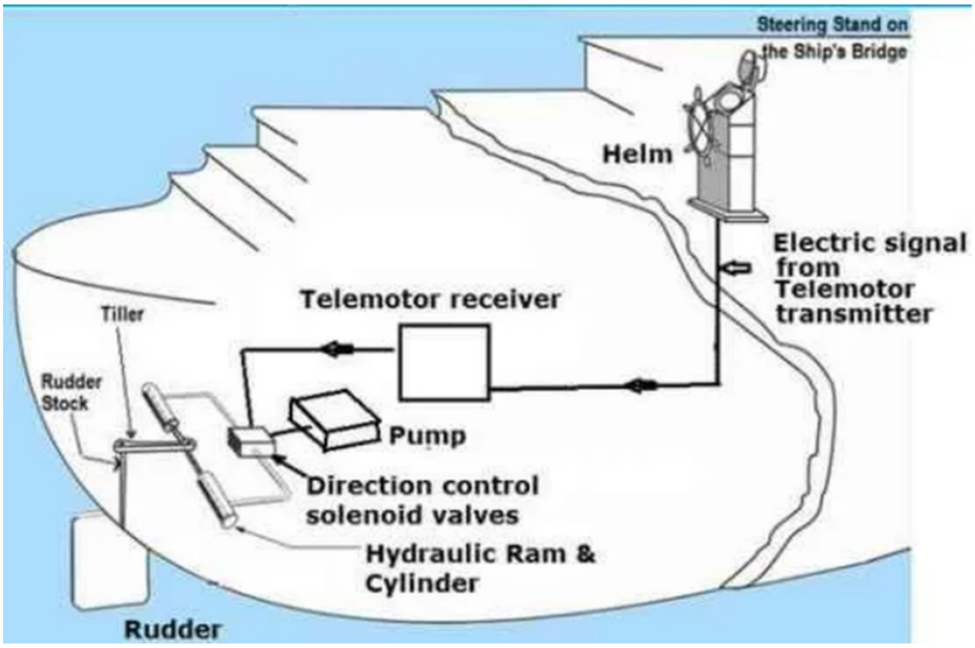


Figure 2.1: Main components of a gear system

the rudder. Hydraulic steering gears are known for their robustness, reliability, and ability to handle the high torque required for large vessels. The key components of a hydraulic steering gear system are hydraulic pumps, hydraulic cylinders, control valves, rudder stock, reservoir, and feedback mechanism. The advantages of hydraulic steering gears are high torque output, ideal for maneuvering large ships, smooth and precise control of the rudder, and reliable operation under varying sea and load conditions. Hydraulic steering gears are used on commercial vessels, tankers, and naval vessels, ensuring accurate and efficient maneuvering, particularly in challenging weather or confined waterways [29].

2. **Electro-Hydraulic Steering Gear:** The electro-hydraulic steering gear is a hybrid system that combines the efficiency of hydraulic steering with the precision of electrical control. It is widely used in modern ships to ensure reliable and efficient rudder movement under varying operational conditions. This system uses electric motors to drive hydraulic pumps, which generate the pressure needed to control the rudder. Key components of an electro-hydraulic steering gear system are electric motor, hydraulic pumps, actuator (hydraulic cylinders), rudder stock, control system, reservoir and pipes. Advantages of electro-hydraulic steering gear are high efficiency, reliability, energy savings, and smooth operation. Electro-hydraulic steering gears are used in a wide range of vessels, including large commercial ships, tankers, and passenger liners. They are especially favored in modern shipping for their reliability, durability, and ability to handle the demanding conditions of maritime navigation [30].

3. **Rotary Vane Steering Gear:** It uses a series of rotating vanes to convert the rotational motion of the steering wheel or tiller into the turning motion of the rudder, which directs the vessel. The key components of a rotary vane steering gear are rotary vanes, hydraulic system, steering wheel or tiller, and rudder. The system is valued for its efficiency, precision, and durability, especially in larger ships. It allows for smoother and more responsive control compared to traditional mechanical or chain-driven systems [31].

2.1.1 Operation Modes of Ship's Steering System

The ship's steering system operates in different modes to ensure safe and efficient maneuverability under various conditions. Based on the open-loop and closed-loop control systems, a ship's steering gear control system can be categorized into Follow-Up and Non-Follow-Up systems [32].

Follow-Up system is the standard steering method that incorporates feedback of the steering angle to the helm. It can be operated either manually or automatically. The ship's heading can be programmed into the autopilot, which continuously compares the actual heading with the desired heading and adjusts the rudder angle accordingly to maintain course.

Non-Follow-Up system used as a backup system, this method involves a single lever for each steering gear unit. When the lever is moved in one direction, the rudder begins to turn and continues to do so until the lever is released or the rudder reaches its operational limit.

2.2 Steering Angle Correction System

A Steering Angle Correction System is a mechanism or technology designed to maintain the desired trajectory of a vehicle or vessel by detecting and correcting deviations in the steering angle. It ensures stability, improves handling, and enhances safety by reducing the effects of factors such as external forces, human errors, or mechanical inaccuracies. The steering angle correction system to prevent capsizing of the ship mainly consists of the several subsections as shown in figure (see figure 2.2).

An integrated sensor system refers to a cohesive setup that combines multiple sensors and their associated components to collect, process, and transmit data in a unified manner. In various applications, such as maritime, automotive, industrial, and environmental monitoring, such systems are used to provide a comprehensive view of the environment or the system's state. These sensors work together to enhance the accuracy and reliability of the collected data, offering more precise and actionable insights for system control, decision-making, or safety improvements. Key features of an integrated sensor system are multi-sensor fusion, real-time monitoring, centralized data

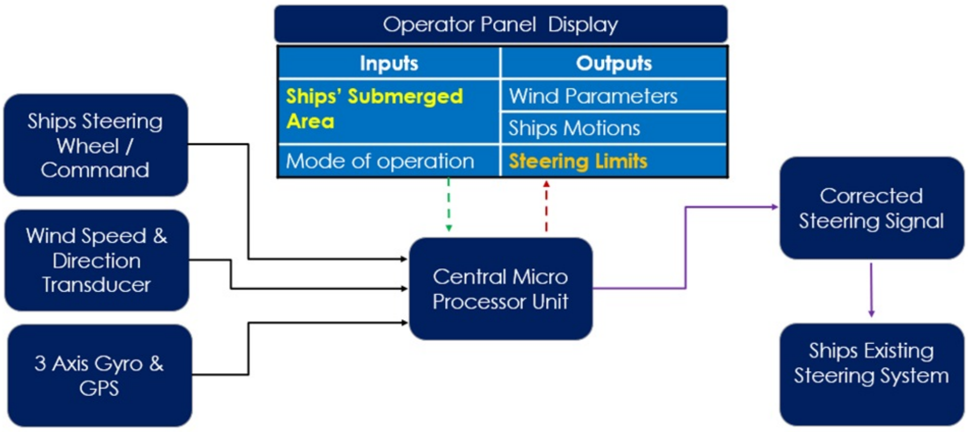


Figure 2.2: Overview of steering angle correction

processing, connectivity and communication, adaptive and intelligent algorithms, and cost and space efficiency. In the context of maritime safety, an integrated sensor system could combine several sensors such as wind speed and direction sensors, gyroscopic sensors, GPS. Data from these sensors is processed by a microcontroller or computer, which uses mathematical models to determine how the ship should adjust its steering to maintain stability, particularly under adverse weather conditions like high winds. This information can then be used to make real-time corrections to the ship's steering angle, ensuring safer navigation and reducing the risk of capsizing or over-steering.

An operator panel is a user interface used to monitor, control, and interact with machines, systems, or processes. It typically serves as the central control point for operators to input commands, monitor system status, and view real-time data, making it an essential part of various industries, such as manufacturing, maritime, and automation. Key features of an operator panel are User Interface (UI) , real-time data visualization, system integration, user-friendly design, safety and emergency features. In the context of maritime navigation, an operator panel could be used on a ship to ensure safe and efficient operation. Wind speed and direction sensors, gyro modules, GPS, and accelerometers continuously provide real-time data about the ship's position, movement, and environmental conditions. The operator panel displays real-time data such as wind speed and direction, ship speed and course, heel angle, rudder angle, and environmental warnings. The panel allows the operator to adjust the ship's course, speed, and steering angles using buttons or a touch interface. It can also display recommendations or automated adjustments based on the wind and ship data, ensuring safe navigation and minimizing the risk of capsizing or over-steering. If wind speed exceeds a predefined threshold, or if the ship starts to heel beyond safe limits, the operator panel triggers visual and auditory alarms to notify the operator. Based on the data and any warnings, the operator can adjust the ship's steering manually, or the system can provide automatic corrections, as dictated by a microcontroller-based control system integrated with the sensors and actuator mechanisms. Key benefits of an operator panel are centralized control, enhanced safety, and ease of use.

The Central Microcontroller Unit (CMU) is the heart of many electronic systems. It is responsible for executing instructions from programs and controlling the flow of information within the system. In systems like embedded devices, automation, and control systems, the CMU plays a critical role in processing data, managing sensor inputs, controlling actuators, and ensuring the proper operation of the entire system. Key functions of a CMU are data processing, control and coordination, interface management, real-time processing, data storage and retrieval, and UI interaction. In ships, the microcontroller process sensor data (wind speed, ship heading, heel angle, etc.) and adjust steering control systems to maintain stability. It could also interface with an operator panel for manual control or display system status.

A ship's steering system is responsible for controlling the vessel's direction by adjusting the rudder or other steering mechanisms. The existing steering system on a ship varies based on the vessel type, size, and operational requirements. It typically consists of a mechanical, hydraulic, or electro-hydraulic system that connects the bridge's steering control to the rudder.

2.3 Material Requirement

The steering angle correction system integrates a set of sensors, including wind speed and direction transducers, gyro modules, and GPS receivers, to continuously monitor environmental factors and navigational parameters of the ship. The collected data from these sensors are processed by a microcontroller (main processing unit), which perform according to the developed mathematical model to assess the wind's impact on the ship's super structure and ship's motion. This developed mathematical model calculates the required adjustments needs to the ship's steering angle to counteract the forces exerted by strong winds, ensuring stability of the ship and safe maneuvering against strong wind condition.

The following are the major components required to collect the data and implement the mathematical model developed to the system.

2.3.1 Microcontroller

A microcontroller is a compact integrated circuit designed for specific control applications. It contains a processor (CPU), memory (RAM, ROM/Flash), and input/output (I/O) peripherals on a single chip. Microcontrollers are commonly used in embedded systems, automation, robotics, and electronic devices. The processor unit is required to process the collected data from various sensors and develop algorithm to prevent over steering with strong wind condition (Algorithm development part will cover in Chapter

3). Considering cost of processor unit, required number of input sensor handling, etc, microcontroller can be selected as a most suitable processor unit for the implementation. Key features of a microcontroller are central processing unit (CPU) , memory: RAM, ROM/Flash Memory, input/output ports (I/O) etc. Timers Counters – Used for time-based operations like delays and event counting. Analog-to-Digital Converter (ADC) – Converts analog signals to digital values. Communication Interfaces: UART, SPI, I2C, CAN, USB for communication with other devices. Power Management – Operates on low power, often with sleep modes. Common microcontroller families are given in the Table 2.1.

Table 2.1: Features of ATmega328 Microcontroller

Sr Number	**Description**	**Remarks**
01	Number of pins	28
02	CPU	RISC 8-Bit AVR
03	Operating Voltage	1.8 to 5.5 V
04	Program Memory	32KB
05	Program Memory Type	Flash
06	SRAM	2048 Bytes
07	EEPROM	1024 Bytes
08	ADC	10-Bit
09	Number of ADC Channels	8
10	PWM Pins	6
11	Comparator	1
12	Packages (4)	8-pin PDIP 32-lead TQFP 28-pad QFN/MLF 32-pad QFN/MLF
13	Oscillator	up to 20 MHz
14	Timer (3)	8-Bit x 2 and 16-Bit x 1
15	Enhanced Power-on Reset	Yes
16	Power Up Timer	Yes
17	I/O Pins	23
18	Manufacturer	Microchip
19	SPI	Yes
20	I2C	Yes
21	Watchdog Timer	Yes
22	Brownout detect (BOD)	Yes
23	Reset	Yes
24	USI (Universal Serial Interface)	Yes
25	Minimum Operating Temperature	$-40C$ to $+85C$

Among the various types of microcontrollers, an Atmega 328 P high-performance microcontroller unit was selected to implement this system. It is capable of handling multiple sensor inputs and performing real-time data processing. ATmega328 is an Advanced Virtual RISC (AVR) microcontroller as shown in figure 2.3). It supports

8-bit data processing and it has 32KB internal flash memory [33].

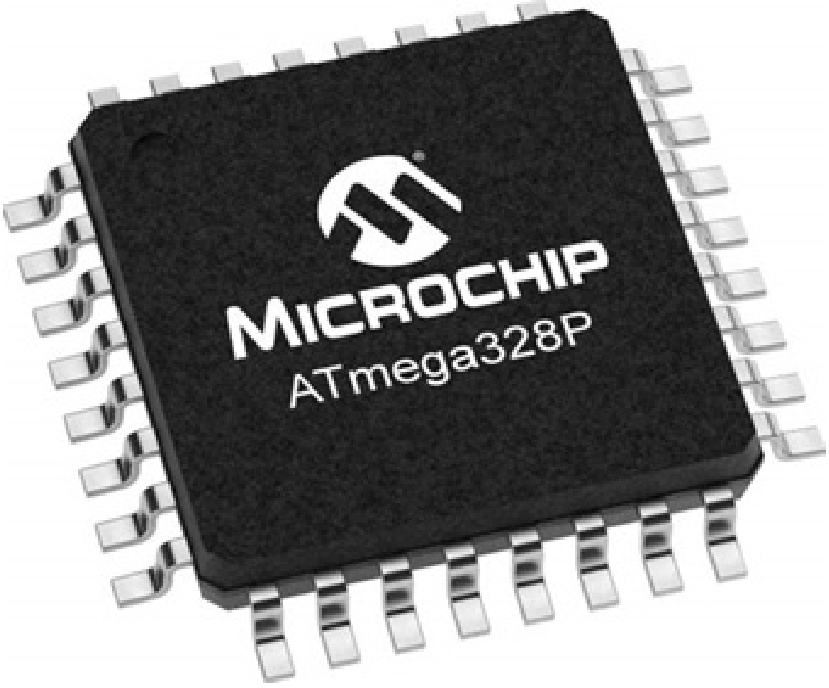


Figure 2.3: AVR Microcontroller

The ATmega328 microcontroller is equipped with 1KB of Electrically Erasable Programmable Read-Only Memory (EEPROM) . This feature ensures that data can be retained even when the power supply to the microcontroller is removed, allowing the device to resume operations seamlessly once power is restored. Additionally, it includes 2KB of Static Random Access Memory (SRAM) , which enhances its processing capabilities.

The ATmega328 stands out in today's market due to its numerous advanced features, including advanced RISC architecture for efficient performance, low power consumption for energy-efficient applications, real-time counter with a dedicated oscillator, six PWM (Pulse Width Modulation) pins for precise control, programmable serial USART for robust communication, programming lock features to ensure software security and high throughput of up to 20 MIPS (Million Instructions Per Second). These attributes collectively make the ATmega328 one of the most popular and versatile microcontrollers available.

2.3.2 Sensors

The accuracy of the corrective steering command as per the developed algorithm is depend on the accuracy of the various sensor inputs coming to the Atmega328P microcontroller. Mainly, following sensors are utilize to collect environmental data.

2.3.2.1 Wind Speed and Direction Sensor

A wind transducer is used to provide precise measurements of both relative and true wind speed and direction for ships and other vessels. When integrated with additional sensors, such as the ship's speed log and heading data from a gyrocompass, the wind transducer delivers the essential wind data needed to calculate true or relative wind speed and direction accurately. This integration ensures reliable and comprehensive wind information for navigation and operational decision-making. The primary types of wind transducers include cup anemometer, vane anemometer, laser doppler anemometer and acoustic resonance anemometer.

Figure 2.4) represents a cup anemometer which consists of three or four hemispherical cups mounted on horizontal arms, and are attached to a vertical shaft. When wind blows past the cups in any horizontal direction, the force of the air flow causes the cups to rotate. The rotational speed of the shaft is roughly proportional to the wind speed. By counting the number of revolutions over a specific time interval, the instrument provides a value that is proportional to the average wind speed. This makes the cup anemometer effective for measuring a wide range of wind speeds. It is often referred to as a rotational anemometer due to its reliance on rotational motion to measure wind velocity [34].

Figure 2.4: Cup Anemometer

Some advantages of cup anemometers are simple and reliable design, not requiring require alignment with wind direction, and works well in various weather conditions. However, cup anemometers can be affected by ice or debris and needs regular calibration for accurate readings. Cup anemometers are widely used in various fields to measure wind speed. Some key applications of cup anemometers include meteorology and weather stations, wind energy industry, aviation and maritime, environmental and climate research, and industrial and safety applications.

A Vane Anemometer is another type of mechanical velocity anemometer as shown in figure 2.5. It features a vertical axis of rotation, and for accurate measurements, the axis must be aligned parallel to the wind's direction, making it horizontally oriented. Since wind direction can change, the vane anemometer is equipped with a wind vane or another mechanism to track these variations. This device combines a propeller and a tail on the same axis, enabling it to measure both wind speed and direction with precision. The fan's rotational speed is tracked by a revolution counter, which, through an electronic chip, converts the data into a wind speed reading. Additionally, if the cross-sectional area is known, the volumetric flow rate can be calculated

Figure 2.5: Vane anemometer

Van anemometers can be used in heating, ventilation, and air conditioning, environmental studies and meteorology, industrial safety, aviation, aerospace, outdoor sports and recreational uses. Advantages of vane anemometers are it measures both wind speed and direction, more stable in continuous airflow measurements, and portable and easy to use in field applications. Some disadvantages of vane anemometers are it must be oriented into the wind for accurate readings, moving parts can wear out over time, and less suitable for extreme weather conditions.

Laser Doppler Anemometers operate based on laser Doppler velocimetry. Unlike traditional anemometers, it is non-intrusive and relies on the Doppler effect to determine velocity without physical contact with the airflow. In this technique, a laser beam is split into two beams, with one directed out of the anemometer. Particles, or deliberately introduced seed material, suspended in the air and flowing with the wind reflect or backscatter the light as they pass through the laser beam. The reflected light is detected and compared to the original laser beam. When the particles move, they cause a Doppler shift in the light, which is used to determine the wind speed. By measuring the shift, the speed of the particles—and consequently, the air around the anemometer—can be calculated with high precision [35]. Figure 2.6 shows laser doppler anemometer.

Figure 2.6: Laser doppler anemometer

Advantages of laser doppler anemometers are non-contact measurement, high precision and resolution, bidirectional measurement, works in transparent fluids, and no calibration required. However, laser doppler anemometers are more costly than traditional anemometers due to laser technology. Some other disadvantages of laser doppler anemometers are requiring seeding particles, sensitivity to optical alignment, and limited to point measurements. Laser doppler anemometers can be applied in aerospace, wind tunnel testing, turbulence and fluid dynamics research, automotive engineering, and industrial flow monitoring.

Figure 2.7shows an acoustic resonance anemometer that is more recent variant of sonic anemometers. Unlike traditional anemometers, it has no moving parts, making it more durable and reliable in harsh environments. Unlike conventional sonic anemometers, which rely on time-of-flight measurements, acoustic resonance sensors use resonating ultrasonic waves within a specially designed cavity to measure wind speed and direction. Inside the cavity, an array of ultrasonic transducers generates separate standing-wave patterns at ultrasonic frequencies [36].

Figure 2.7: Acoustic resonance anemometer

As wind flows through the cavity, it causes a phase shift in the waves. By measuring the phase shift in the signals received by each transducer and processing the data mathematically, the sensor can accurately determine the horizontal wind speed and direction.

Advantages of acoustic resonance anemometers are no moving parts, high accuracy, fast response, compact and robust design, minimal maintenance, and works in extreme temperatures, rain, and even icy conditions. However, higher cost, sensitive to external noise, limited measurement range are some disadvantage of acoustic resonance anemometers. Acoustic resonance anemometers can be applied in marine and offshore industry, aviation and aerospace, meteorology and weather stations, and industrial safety and monitoring.

Among the various wind transducers commonly used in the marine industry, including cup anemometers and laser Doppler anemometers, the vane anemometer has been selected for this research. This choice is based on its well-established reliability, cost-effectiveness, and uninterrupted performance over the past decades in marine applications [37]. Its ability to provide consistent wind speed and direction measurements makes it a preferred option for long-term use in maritime environments.

For the in-house simulation, two 10K potentiometers will be used to simulate wind direction and wind speed, generating data similar to the output of a vane anemometer.

2.3.2.2 Gyroscope

A gyroscope is a device as shown in figure 2.8 that utilizes a rapidly spinning wheel or a circulating beam of light to detect and measure deviations in an object's orientation from its desired position. This precision instrument is widely used in applications such as compasses and autopilot systems for ships and aircraft. Additionally, gyroscopes are critical components in the steering mechanisms of torpedoes, as well as in inertial guidance systems for space launch vehicles, ballistic missiles, and orbiting satellites [38]. Their ability to provide accurate orientation and stability makes them essential in navigation and control systems.

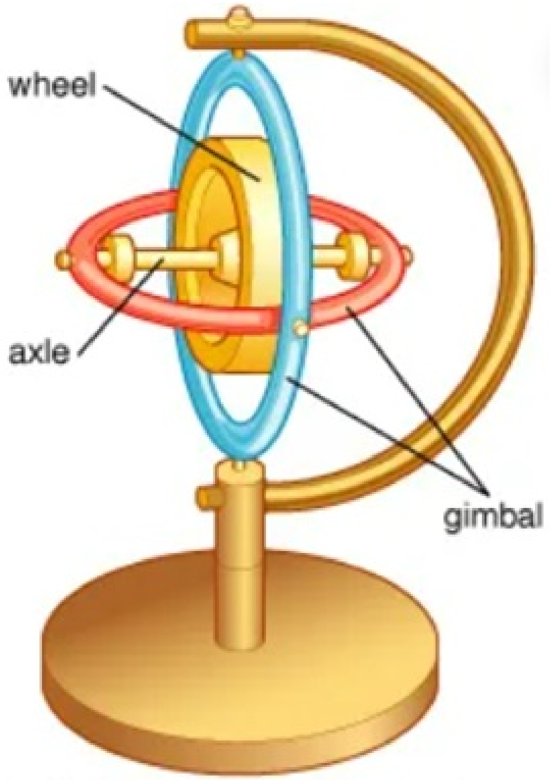


Figure 2.8: Internal arrangement of Gyroscope

The gyroscope is one of the most critical pieces of navigation equipment used to determine a ship's heading in the marine industry. Various types of gyroscopes are utilized to ensure accurate navigation and facilitate smooth voyages at sea.

The working principle of the mechanical gyroscope is based on the conservation of angular momentum, making it one of the most widely recognized types of gyroscopes. A mechanical gyroscope relies on ball bearings to facilitate its spinning motion. However, due to their noisier operation, these gyroscopes are increasingly being replaced by modern alternatives. Despite this, mechanical gyroscopes continue to find applications in the navigation of large aircraft and missile guidance systems.

Mechanical gyroscopes work without electronic components, making it robust in extreme conditions. Moreover, once spun, it maintains motion with minimal energy loss. Mechanical gyroscopes are useful for applications requiring stability and directional accuracy. Some disadvantages of mechanical gyroscopes are mechanical components experience gradual degradation over time, traditional gyroscopes can be bulky compared to modern alternatives, and external disturbances can cause slow drifts, requiring correction mechanisms.

Unlike mechanical gyroscopes, optical gyroscopes do not rely on ball bearings or rotating wheels, nor are they based on the conservation of angular momentum. Instead, they operate using two optical fiber coils arranged in different orientations to detect changes in angular velocity. Figure 2.9 represents an optical gyroscope. Since optical gyroscopes have no moving parts, they are highly durable and are commonly used in modern spacecraft and rockets.

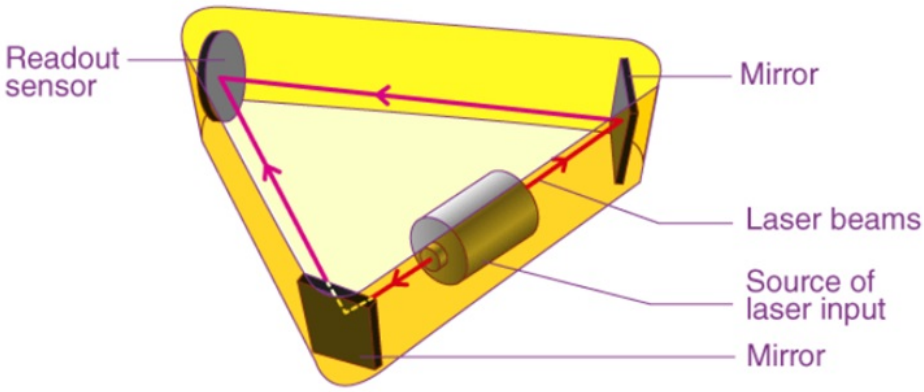


Figure 2.9: Optical Gyroscope

There are several types of optical gyroscopes, but the most common are fiber optic gyroscope, ring laser gyroscope, and free-space optical gyroscope. Unlike mechanical gyroscopes, optical gyroscopes have no moving parts, making them highly reliable and reducing wear and tear. Optical gyroscopes can provide extremely precise measurements, even at low angular velocities. Optical gyroscopes are less prone to mechanical failures due to the absence of physical components. Particularly fiber optic gyroscopes are compact and can be miniaturized for portable applications. Modern optical gyroscopes are designed to consume minimal power, making them suitable for long-term use in remote or battery-powered applications. However, optical gyroscopes tend to be more expensive than mechanical gyroscopes, especially in high-precision applications. Moreover, optical gyroscopes can be sensitive to temperature changes, vibrations, and other environmental factors, which may require additional calibration or shielding. The technology and signal processing required for optical gyroscopes are more complex compared to mechanical gyroscopes. While small-scale fiber-optic gyroscopes are compact, the setup for larger systems can be bulkier than some alternatives. Optical gyroscopes can be applied in aerospace and navigation systems, autonomous vehicles, defense and military, seismology, geodesy and earth observation, robotics and virtual reality.

In contemporary technology, Micro-Electro-Mechanical Systems (MEMS) gyroscopes have become increasingly prevalent due to their versatility and growing adoption. MEMS sensors are utilized in a wide range of applications, including mobile phones, robotics, automotive systems, bioengineering, aeronautics, and communication. MEMS inertial sensors are widely used in consumer-grade systems due to their lower cost, compact size, reduced weight, and decreased power consumption. There are two primary types of MEMS inertial sensors: Quartz-based MEMS Gyroscopes and Silicon-based MEMS Gyroscopes. MEMS gyroscopes continue to drive innovation in both consumer and industrial applications due to their efficiency and scalability. Figure 2.10 shows a MEMS Gyroscope.

Figure 2.10: MEMS Gyrosope

Mechanical gyroscopes are widely used in the marine industry for navigation purposes. In the simulation phase of this project, an in-house setup was utilized, considering factors such as product cost and ease of handling. To monitor the ship's orientation, the ADXL345 Triple Digital Accelerometer Module was employed.

For actual implementation, the system can seamlessly integrate with the ship's existing gyrocompass, eliminating the need for additional hardware purchases.

In the in-house simulation, a 10K potentiometer was used to simulate the ship's heading, providing data similar to that of a MEMS gyroscope. This approach allowed for effective testing and validation of the system before deployment.

2.3.2.3 GPS Receiver

The Global Positioning System (GPS) has played a pivotal role in the rapid advancement of marine operations, particularly in search and rescue missions. GPS offers the most reliable and accurate means for mariners to navigate, measure speed, and determine their precise location, leading to enhanced safety and efficiency across the globe [39]. Figure 2.11 represents a NEO 6M high-precision GPS module.

Figure 2.11: NEO 6M High-precision GPS module

For ship officers, knowing the vessel's position is crucial both in open sea and in congested harbors or waterways. While navigating on the high seas, precise information about position, speed, and heading ensures that the vessel reaches its destination in the most efficient, safe, and timely manner possible, considering prevailing conditions. The necessity for accurate positional data becomes even more critical when vessels are departing from or approaching ports. In these settings, where vessel traffic and other waterway hazards are more concentrated, maneuvering becomes more complex, and the likelihood of accidents increases. Therefore, reliable GPS data not only supports safe navigation but also contributes significantly to preventing potential collisions and improving overall maritime safety.

For the implementation of this project, the NEO 6M High-Precision GPS module was used to provide real-time navigational data, including the ship's position and speed. Accurate ship speed is crucial for the success of this project.

As an alternative, a 10K potentiometer has been chosen to simulate the ship's speed. The potentiometer will generate a speed value similar to the GPS data output, allowing the simulation to replicate the conditions of actual maritime navigation.

2.3.3 LCD Display

An LCD display, as shown in the operation panel in Figure 2.12 has been provided to input additional data required for the algorithm and to select the mode of operation. It also displays essential outputs such as wind parameters, the steering angle command, rudder angle, and other vital data.

Figure 2.12: 16×4 LCD Display

A 16×4 LCD display is an alphanumeric module that can display 16 characters per line across 4 lines, providing a total of 64 characters at a time. This type of display is commonly used in embedded systems, industrial control panels, and other applications where a compact yet readable output is necessary. The 16×4 display is adequate to show the essential outputs from the system, as described above.

In a real-world application, a Human-Machine Interface (HMI) display could be employed to both receive output data from the system and feed inputs into it [40].

2.3.4 Actuators

Actuators are devices responsible for converting control signals (typically electrical or pneumatic) into mechanical motion or force [41]. They are commonly used in automated systems to perform actions such as moving, opening, closing, or adjusting components based on inputs from a controller. Actuators can be classified according to the type of energy they use.

An electric actuator is a type of actuator that converts electrical energy into mechanical motion. It is commonly used in a wide range of applications where precise movement and control are required. Electric actuators are essential components in various systems, such as robotics, industrial automation, heating, ventilation, and air conditioning (HVAC) systems, and automotive systems. The rotational motion of the motor is often transformed into linear motion using a gear mechanism, lead screw, or belt. This can also involve rotating parts that create movements such as lifting, pushing, or turning. The actuator's motion can be precisely controlled using a control system that adjusts the motor's speed, position, or force, often involving sensors or feedback mechanisms. Rotary electric actuators, linear electric actuators, stepper motor actuators, and servo actuators are some types of electric actuators. Electric actuators offer high precision in motion control, especially when paired with feedback systems or sensors. They convert electrical energy into mechanical motion efficiently, reducing energy loss. Unlike hydraulic or pneumatic actuators, electric actuators do not rely on fluids, making them cleaner and easier to maintain. Electric actuators are typically more compact and lighter than their hydraulic and pneumatic counterparts. They are easy to integrate with digital control systems, providing automated and programmable operation. From industrial machinery to consumer products, electric actuators serve in numerous sectors, offering versatile functionality. Some disadvantages of electric actuators are limited force output, heat generation, power supply dependency, cost of components, and speed limitations. Electric actuators are applied in industrial automation, robotics, automotive, HVAC systems, medical equipment, home automation, aerospace and defense, energy and utilities. Electric actuators are widely used across various industries due to their precision, energy efficiency, and ease of integration with digital control systems. While they may not generate as much force as hydraulic actuators, their compact size and versatility make them ideal for many applications, particularly where precision and control are crucial. With ongoing advancements in electric motor technology, their performance continues to improve, making them a go-to choice in automation and motion control systems.

A pneumatic actuator is a type of actuator that uses compressed air to create mechanical motion. Pneumatic actuators are widely used in automation and industrial processes due to their high speed, simplicity, and reliability. They are commonly used to control the movement of mechanical systems by converting the energy stored in compressed air into linear or rotary motion. Pneumatic actuators operate by using compressed air to create force that drives a mechanical component. The actuator is connected to a source of compressed air, usually from a compressor. Compressed air is directed into a chamber of the actuator. The pressure of the air creates force that moves a piston or diaphragm inside the actuator. The pressure moves a piston back and forth inside a cylinder, creating linear motion. The compressed air is used to turn a vane or rotor, generating rotational motion. The air is exhausted from the actuator after it has created the desired motion, and the cycle repeats. There are two types of pneumatic actuators called linear pneumatic actuators, and rotary pneumatic actuators. Advantages of pneumatic actuators are high speed, simplicity, reliability, clean operation, cost-effective, and safety. Some disadvantages of pneumatic actuators are limited force output, air supply dependency, efficiency, limited Precision, and environmental sensitivity. Pneumatic actuators can be applied in automation and manufacturing, control systems, valve actuation, transportation, robotics, HVAC systems, medical devices, and agricultural equipment.

A hydraulic actuator is a device that uses pressurized hydraulic fluid to create mechanical motion. Hydraulic actuators are known for their ability to generate significant force, making them ideal for heavy-duty applications in industries like construction, manufacturing, aerospace, and automotive. These actuators can provide linear or rotary motion, depending on the design and application. Hydraulic actuators work by using pressurized hydraulic fluid to move a piston or motor within a cylinder or housing. The force generated by the pressure of the fluid creates mechanical motion. A hydraulic pump delivers pressurized fluid to the actuator from a reservoir. The pressurized fluid enters the actuator's cylinder or motor, where it applies force on a piston or diaphragm. The pressure pushes the piston (in a linear actuator) or rotates a motor shaft (in a rotary actuator), generating mechanical motion. After the fluid has acted on the piston or motor, it is exhausted back to the reservoir or pump to complete the cycle. Linear hydraulic actuators, and rotary hydraulic actuators are two main types of hydraulic actuators. Advantages of hydraulic actuators are high force output, compact design, smooth operation, continuous operation, fine control, and high efficiency. Disadvantages of hydraulic actuators are complexity and maintenance, environmental impact, cost, size, weight, noise, and temperature sensitivity. Hydraulic actuators can be applied in construction and heavy machinery, automotive, aerospace, industrial equipment, marine, robotics and automation, and renewable energy.

A thermal actuator is a type of actuator that uses temperature changes to create mechanical motion. These actuators operate based on the expansion or contraction of materials in response to temperature changes, typically using the properties of materials such as wax, metal, or polymer, which expand or contract when heated or cooled. Thermal actuators are widely used in applications where precise control of movement is required in response to temperature changes. Thermal actuators function by utilizing the thermal expansion or contraction of materials. A thermal actuator is exposed to a heat source (either externally or by an internal heating element). Then the temperature of the actuator rises. The material used in the actuator such as a wax, metal, or polymer expands or contracts in response to the change in temperature. The expansion or contraction of the material causes a mechanical movement, such as the extension or retraction of a piston, the bending of a metal strip, or the rotation of a component. When the heat source is removed or the temperature decreases, the material contracts and returns to its original position, causing the actuator to reverse the movement. There are different types of thermal actuators such as wax-based thermal actuators, bimetallic thermal actuators, shape memory alloy (SMA) actuators, and thermal gas expansion actuators. Simple design, no need for external power supply, compact, lightweight, cost-effective, precise temperature control are some advantages of thermal actuators. Disadvantages of thermal actuators are slow response time, limited force output, temperature sensitivity, limited durability, not suitable for continuous operation. Thermal actuators are applied in thermostats and temperature control, automotive, aerospace, consumer electronics, medical devices, robotics, and smart clothing.

A prototype model was designed to implement the system's output, with an electric servo motor used to control the steering angle. The servo motor was chosen for its precise control over angular displacement, making it ideal for applications where accurate adjustments to the steering are required. The motor receives signals from the control system, adjusting the rudder angle based on the desired heading or steering command. This prototype serves as a proof of concept for the system, enabling real-time testing of navigation commands and ensuring the integration of sensor data, such as speed and wind parameters, with the steering control mechanism. Through this model, the effectiveness and responsiveness of the actuator in controlling the vessel's movement can be evaluated, and further improvements can be made to enhance performance and reliability in real-world scenarios.

2.4 Standards Data Formats

Standards data formats refer to universally recognized and established methods of structuring, representing, and storing data for various applications. These formats ensure interoperability, consistency, and ease of exchange across systems, industries, and software tools. These standards are critical in fields such as engineering, science, healthcare, and business. When selecting a data format for a particular case, we should consider several factors such as data complexity, human-readability, performance, interoperability, size and efficiency.

The establishment of standardized practices in the marine environment is essential for ensuring safety, efficiency, and interoperability. Given the complexity of maritime operations and the variety of technologies involved, standards play a critical role in mitigating risks and enhancing overall operational effectiveness. By adhering to proven guidelines, equipment and systems can operate more reliably and safely.

A key example of such a standard is the National Marine Electronics Association (NMEA) standard, which defines protocols for communication between marine electronics [42]. The NMEA standard serves as a foundation for ensuring compatibility and interoperability between various devices and systems used in marine navigation, monitoring, and communication. These devices, which include GPS receivers, radar systems, wind transducers, and depth sounders, can seamlessly share and exchange data using a common communication protocol.

By providing a unified language for marine electronics, the NMEA standards contribute to more reliable system performance, easier troubleshooting, and smoother integration of new technologies. This standardization ensures that systems from different manufacturers can work together effectively, which is particularly important for complex maritime operations. As a result, the NMEA standards help to enhance safety by minimizing the potential for communication errors, improving situational awareness, and supporting more informed decision-making on the water.

The NMEA 0183 standard is one of the older, yet still widely used protocols for marine communication [43]. It allows serial communication between marine devices in a simple ASCII text format. Operating as a single-ended, one-way communication system, NMEA 0183 typically functions at a data rate of 4,800 baud, although higher rates, such as 38,400 baud, are used for specific applications like Automatic Identification Systems (AIS). The protocol enables communication between one "talker" (a device transmitting data) and multiple "listeners" (devices receiving data), making it ideal for basic systems such as GPS receivers, depth sounders, and other navigational instruments. Despite its longevity and reliability, NMEA 0183 has bandwidth limitations, restricting its ability to support more complex, data-intensive modern systems. As a result, while it remains useful for straightforward applications, newer protocols are often needed to meet the demands of more advanced marine electronics.

The NMEA 2000 standard is a multi-talker, multi-listener protocol based on Controller Area Network (CAN) bus technology [44]. It provides significantly higher data rates up to 250 Kbps making it far more capable of supporting the real-time data exchange required for modern marine systems. Unlike NMEA 0183, which is limited to one-way communication, NMEA 2000 allows multiple devices to communicate simultaneously, making it ideal for complex systems where data from GPS, radar, sonar, autopilot systems, and other navigational equipment must be shared seamlessly. NMEA

2000 is designed to support sophisticated setups, providing robust communication even when multiple devices are connected to the same network. Its plug-and-play capability makes it easier to expand the system by adding new devices without requiring complex configuration, making it highly scalable for larger or more complex vessels. As a result, NMEA 2000 has become the preferred protocol for modern marine electronics, offering flexibility, reliability, and ease of integration across a wide range of applications.

NMEA OneNet is an Ethernet-based protocol designed to complement the NMEA 2000 standard by offering significantly higher data transfer rates [45]. Utilizing standard Ethernet technology, OneNet supports more data-intensive applications, including high-definition radar, sonar, and even video transmissions. With its high bandwidth capabilities, OneNet is particularly suited for modern vessels that require fast, seamless communication between advanced systems. OneNet's ability to handle large data streams makes it ideal for applications such as real-time video feeds from onboard cameras, high-speed internet connectivity, and the integration of advanced navigational tools that demand substantial data exchange. It enables more efficient data sharing across multiple systems onboard, providing enhanced system performance and greater operational flexibility. As the maritime industry moves toward more sophisticated, data-driven solutions, NMEA OneNet plays a critical role in ensuring the fast, reliable transmission of large data volumes necessary for modern vessel operations.

The variation NMEA 0183-HS (High Speed) of the NMEA 0183 standard is designed to accommodate higher-speed communications, with a data rate of 38,400 baud. It is particularly well-suited for Automatic Identification Systems (AIS) and other devices that require faster data transfer than the standard NMEA 0183 protocol can support. By offering increased bandwidth, this enhanced version of NMEA 0183 enables vessels to rely on real-time identification and tracking information from AIS, while maintaining a simpler communication setup compared to more complex protocols. This makes it an ideal solution for vessels that need to ensure efficient data exchange for navigation and safety without the need for advanced or expensive communication systems.

Together, these NMEA standards offer a range of solutions tailored to various vessel sizes and operational complexities, ensuring reliable communication between critical electronic systems onboard ships. By providing protocols that scale from basic to advanced applications, they enable seamless data exchange, improving system integration, operational efficiency, and safety across different types of maritime environments.

2.4.1 Standard Data Sentence for Vane Anemometer

The NMEA data format for an anemometer typically uses the Marine Wind Velocity (MWV) sentence to convey wind-related information. The MWV sentence contains both wind speed and direction data, and it can represent either the apparent wind (relative to the ship's heading) or the true wind (absolute direction and speed).

A typical MWV sentence structure for an anemometer in NMEA format is as follows:

$$\$WIMWV, wind\_angle, reference, wind\_speed, wind\_speed\_unit,$$
$$status * checksum$$

This is the breakdown of the sentence fields:

$WI: Prefix for weather instruments - may vary by manufacturer

MWV: Sentence identifier for "Wind Speed and Angle”

Wind_angle: Wind angle in degrees (000 to 359), measured relative to the reference

reference: Indicates the reference for the wind angle. Possible values are:

R: Relative (apparent wind, i.e., wind relative to the vessel's movement).

T: True (true wind, i.e., wind unaffected by the vessel's movement).

Wind_speed: Wind speed value.

wind_speed_unit: Unit for wind speed, which can be:

K: Kilometers per hour.

M: Meters per second.

N: Knots.

status: Status of the data:

A: Data is valid.

V: Data is invalid.

checksum: Ensures the integrity of the data. It is a hexadecimal value that follows the asterisk

2.4.2 Standard Data Sentence for Gyroscope

The NMEA sentence typically used for a MEMS gyroscope to report heading and rate of turn information is the HDG or HDM sentence for heading data and the ROT sentence for rate of turn. Here is a typical HDG sentence structure for a MEMS gyro in NMEA format;

$$\$HCHDG, heading, magnetic\_deviation, deviation\_direction, magnetic\_variation, \\ variation\_direction * checksum$$

This is the breakdown of the sentence fields:

$HC: Prefix indicating the device

HDG: Sentence identifier for "Heading, Deviation, and Variation."

heading: The current heading in degrees relative to magnetic north (000.0 to 359.9)

magnetic_deviation: The amount of deviation in degrees caused by the ship's magnetic fields (may be blank if unknown)

deviation_direction: Direction of magnetic deviation:

E: East.

W: West.

magnetic_variation: The amount of variation in degrees between true north and magnetic north (may be blank if unknown).

variation_direction: Direction of magnetic variation:

E: East.

W: West.

checksum: Ensures the integrity of the data.

2.4.3 Standard Data Sentence for GPS

For GPS data, the NMEA 0183 format commonly uses the GGA (Global Positioning System Fix Data) sentence, which provides essential fix data such as time, position, and fix quality. Here is a typical HDG sentence structure for a MEMS gyro in NMEA format:

$$\$GPGGA, UTC\_time, latitude, N/S, longitude, E/W, fix\_quality, num\_satellites, HDOP, altitude, M, geoidal\_separation, M, dgps\_age, dgps\_station\_id * checksum$$

This is the breakdown of the sentence fields:

$GP: Prefix indicating GPS data.

GGA: Sentence identifier for "Global Positioning System Fix Data."

UTC_time: Time of fix in UTC (hhmmss.sss format).

N/S: Hemisphere indicator for latitude:

N: North.

S: South.

longitude: Longitude in degrees and minutes (dddmm.mmmm format).

E/W: Hemisphere indicator for longitude:

E: East.

W: West.

fix_quality: GPS fix quality indicator:

0: Invalid fix.

1: GPS fix.

2: DGPS fix.

num_satellites: Number of satellites used in the fix.

HDOP: Horizontal dilution of precision (a measure of the accuracy).

altitude: Altitude above mean sea level in meters.

M: Unit of altitude (always meters).

geoidal_separation: Geoidal separation (the difference between the WGS-84 ellipsoid and mean sea level) in meters.

M: Unit of geoidal separation (always meters).

dgps_age: Age of differential GPS data (if applicable).

dgps_station_id: ID of the differential GPS station (if applicable).

checksum: Ensures the integrity of the data.

CHAPTER 3

MATHEMATICAL MODELING

Mathematical modeling plays a crucial role in the correction of a ship's steering angle for safe maneuvering, especially in challenging conditions such as strong winds. Using a microcontroller, mathematical models enable precise control over the ship's steering system by providing a structured way to predict and adjust the ship's behavior. In this chapter, present a mathematical model that can be used for correction of ships' steering angle against strong winds.

3.1 Mathematical Modeling for Correction of a Ship's Steering Angle

Mathematical models describe the physical behavior of a ship under various conditions by taking into factors such as hydrodynamics, aerodynamics, inertia and momentum [46–50]. Understanding these dynamics allows for predicting how the ship will behave when affected by external forces like strong winds. In strong winds, ships experience external forces that can push them off course. Figure 3.1 represents external forces on a ship. Mathematical models can simulate these forces and help calculate the required counter-steering to maintain a safe trajectory which includes wind angle and intensity and environmental conditions. With this data, a mathematical model can predict the corrective steering angle required to counteract the drift caused by the wind, helping the ship stay on course.

Once a model of the ship's dynamics and the external forces is developed, it can be used to design a feedback control system. The mathematical model serves as a basis for tuning these controllers. The microcontroller implements the control algorithms derived from the model, adjusting the steering angles of the rudder or helm to ensure safe navigation.

Before implementing a real-time control system, mathematical models allow for extensive simulation of different conditions (e.g., varying wind strengths, etc) without actual risk. By testing the model, engineers can fine-tune the algorithms used in the microcontroller to ensure the ship will safely maneuver in diverse environments.

Ships often need to perform complex maneuvers, such as turns or course corrections, to avoid obstacles or adjust to changing wind patterns. Mathematical models help optimize steering angles and responses, ensuring efficiency and stability. The microcontroller, with its computational ability, applies the model-based corrections in real-time, enabling rapid and accurate adjustments.

Mathematical models allow the microcontroller to adapt in real-time to changing conditions. For example, if the wind strength or direction shifts unexpectedly, the

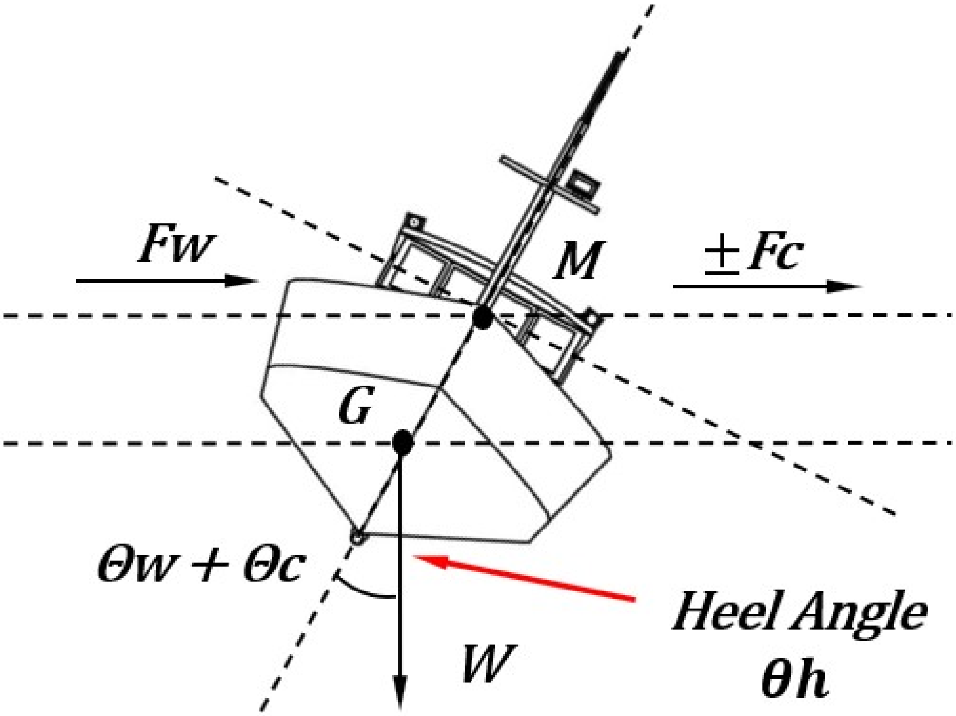


Figure 3.1: External Force on Ship

microcontroller can quickly update its control commands based on the model's predictions, ensuring safe and stable navigation at all times.

The ultimate goal of a mathematical model is to increase the safety and reliability of the ship's maneuvering system. By ensuring the ship responds appropriately to the external disturbances caused by strong winds, mathematical models reduce the likelihood of accidents such as capsizing, collision, or running off course.

3.2 Model Description

In this section, describe the mathematical model that was developed to correct the steering angle of a ship against strong winds.

The mathematical model of the steering correction system is designed to ensure the vessel's stability and safe maneuvering, particularly in adverse environmental conditions. This model incorporates key ship characteristics and forces that influence steering dynamics. The following elements are considered in detail:

1. **Stability Records – GZ Curves:** The GZ curve (righting arm curve) is fundamental in assessing the ship's stability [51–55]. It provides the relationship between the ship's righting moment and the angle of heel by providing information about the initial stability, angle of maximum stability, range of stability, dynamic stability, angle of vanishing stability (AVS) : maximum righting arm

(GZ_max). The GZ data, provided by the manufacturer is integrated into the mathematical model to define stability limits under various operating conditions. This ensures the steering correction system does not introduce excessive heeling moments that could lead to instability. By incorporating the GZ curve, the model dynamically adjusts the steering angle to maintain the ship within its safe range of stability during maneuvers. Figure 3.2 represents the GZ curve.

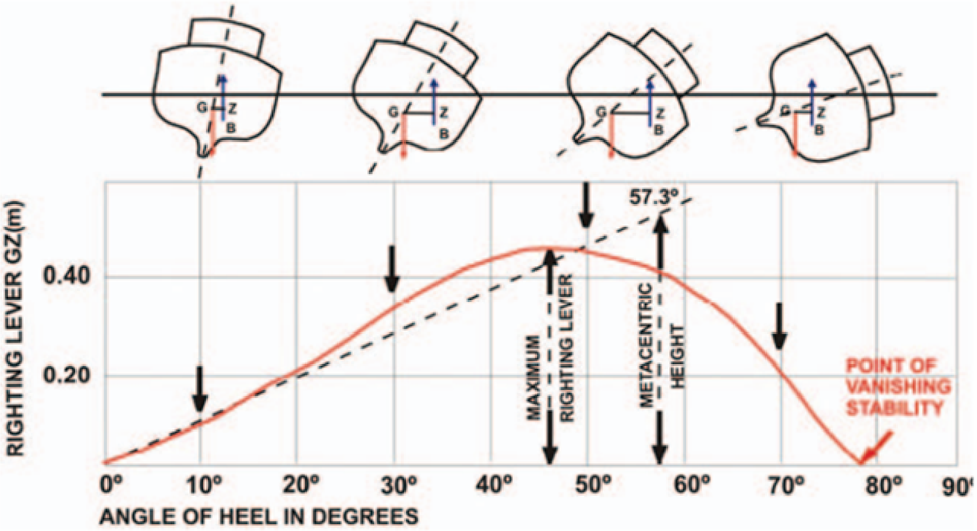


Figure 3.2: GZ Curve

2. **Ships displacement:** The ship's displacement, or the total weight of water displaced by the vessel, is a crucial factor in determining the forces acting on the hull [56, 57]. There are several types of displacement used in different contexts. The most commonly referred to are lightweight displacement, loaded displacement, and deadweight. The lightweight displacement represents the mass of the ship's hull, machinery, equipment, and crew, but excluding cargo, fuel, ballast, and water. Lightweight displacement is crucial for determining the vessel's center of gravity and the distribution of weight that affects its stability. This value is essential during the design and construction phases of the ship, as it forms the basis for determining its capacity to carry additional weight. Loaded displacement is the total displacement when the ship is fully loaded with cargo, fuel, ballast, passengers, and other materials. Loaded displacement is the actual weight of the ship under operational conditions. This value is important for understanding how much weight the ship is carrying, including all of its contents. Loaded displacement affects the ship's draft, which influences its ability to navigate in shallow waters. Deadweight is the total weight the ship can carry, including cargo, fuel, passengers, crew, and provisions, but excluding the weight of the ship itself. This value is often used to determine the carrying capacity of

the ship. Deadweight is a key metric for commercial ships, as it determines the amount of cargo the vessel can transport. The displacement of a ship determines its buoyancy, which is the ability of the ship to float. According to Archimedes' Principle, an object will float if the weight of the water it displaces is equal to the weight of the object itself. A larger displacement generally indicates a larger hull volume, which can contribute to greater stability. However, ship stability depends on other factors such as the center of gravity and metacentric height. Displacement affects both the inertia and hydrodynamic forces experienced during steering. Larger displacements require greater steering forces to counteract external disturbances such as wind and waves. This parameter is used in the model to calculate the magnitude of the forces acting on the ship and to adjust the steering correction accordingly.

3. **Ship's speed:** The ship's speed is directly linked to the forces experienced during steering, particularly the centrifugal force generated in circular motion. Several factors influence a ship's speed, from the design and power of the vessel to the environmental conditions in which it operates. The power generated by the ship's engine is one of the most direct influences on speed. More powerful engines provide greater thrust, allowing the ship to move faster. The efficiency of the ship's propeller is critical. A propeller converts the engine's power into thrust, and the design of the propeller affects how effectively this energy is used to propel the ship through the water. The shape of the hull and the materials used in its construction affect the frictional resistance the ship encounters as it moves through water. Ships with smoother, more hydrodynamic hulls experience less drag and can achieve higher speeds. The hull design determines the ship's ability to cut through water. Vessels with more streamlined hulls such as fast ferries or military ships are able to achieve higher speeds. Larger ships with wider hulls generally experience more resistance and may be slower than smaller ships of the same type. The weight of the ship, or displacement, directly impacts its speed. Heavier ships displace more water and thus face more resistance. Ships with larger displacement may require more power to maintain higher speeds, and their maximum speed can be limited by their size. Wind can either help or hinder a ship's speed. A stern wind can provide a speed boost, while a headwind creates additional resistance and reduces the effective speed. Crosswinds can also affect the ship's course and maneuverability. The presence of ocean currents can have a significant impact on ship speed. If the current is flowing in the same direction as the ship, it will increase the speed over ground. Conversely, a current flowing opposite to the ship's direction will slow it down.The type of fuel used by the ship and its rate of consumption play a role in the ship's operational speed. Ships running on more efficient or higher-energy fuels can operate faster

for longer periods. Managing fuel consumption is essential for maintaining optimal speed while ensuring efficiency. The load at which the engine operates can impact speed. Operating at full throttle provides maximum speed, but it may also result in higher fuel consumption. Operating at reduced loads conserves fuel but reduces speed. In shallow waters, ships with shallow drafts may be able to move faster due to reduced drag. However, in deep waters, the ship might need to have more power to maintain speed. Ship's speed can be measured by a speed log, GPS systems, and pitometer log. The mathematical model considers Speed Over Ground (SOG) and Rate of Turn (ROT) to determine the turning radius and corresponding forces during maneuvers [58]. Higher speeds increase the centrifugal force, which must be balanced with appropriate steering corrections to prevent over-steering or excessive heeling.

4. **Wind force:** Wind forces play a critical role in the stability and maneuverability of ships. Understanding how wind interacts with a vessel's design, weight distribution, and environmental factors is crucial for ensuring safe and efficient navigation, especially in adverse conditions. Wind forces on a ship are typically classified into two primary components called lateral wind force, and longitudinal wind force. Lateral wind force is the force exerted by the wind acting horizontally on the side of the ship. Lateral wind forces can cause the ship to heel (tilt) towards the side exposed to the wind. This effect is particularly significant when the ship is operating in open waters or has a large wind profile such as a high superstructure or large cargo. Excessive heeling due to side winds can lead to instability, especially in high winds, and might even cause capsizing in extreme cases. Ballast, hull design, and stabilization systems are used to resist the heeling force and improve stability. Longitudinal wind forces are the wind forces acting along the ship's length, either from the front (headwind) or from behind (stern wind). A headwind increases the resistance the ship faces while moving forward, reducing its speed and making it harder to maintain control. A Stern wind, on the other hand, can push the ship forward, reducing fuel consumption and increasing speed. However, it can also complicate stopping or turning maneuvers because the ship gains speed quickly. In both headwinds and stern winds, the ship's ability to maintain a course and make adjustments such as stopping, turning can be influenced by wind pressure, particularly in strong winds. Crosswind force is a wind that comes from the side, potentially pushing the vessel off course. It is similar to lateral wind force but more likely to impact maneuvering at lower speeds such as when docking or navigating narrow channels. Crosswinds can cause drift or the ship to veer off its intended path. This is particularly noticeable when the ship has large exposed areas such as a tall superstructure or a wide beam. The model incorporates wind speed and direction,

obtained from wind transducers, to calculate the wind-induced heeling moment [59]. This allows the system to calculate corrective steering angles to counteract wind effects dynamically.

5. **Forces in circular motion:** Circular motion forces, or centrifugal forces, arise due to the ship's turning motion and depend on the ship's speed and turning radius [60]. While centripetal force is the key force in circular motion, there may be other forces such as tension force and normal force are involved depending on the situation. The model balances the centrifugal force with the rudder force to maintain stability and prevent over-steering.

The system integrates data from sensors, including wind transducers, gyroscopes, and GPS modules to calculate these forces in real-time. By combining these parameters, the mathematical model determines the required rudder angle adjustments to counteract external forces while keeping the vessel within safe stability limits. The microcontroller continuously evaluates the interaction of wind force, circular motion forces, and the ship's stability characteristics (e.g., GZ curve) to generate corrective steering commands. This comprehensive approach ensures the steering correction system adapts dynamically to varying environmental conditions, enhancing the vessel's safety and performance in real-time.

When a ship is turning, various forces act on it due to its motion, the steering mechanism, and the ship's interaction with the water. Turning creates dynamic forces that influence the stability, trajectory, and overall performance of the ship. Understanding these forces is essential for ensuring that the ship turns efficiently while maintaining stability and avoiding capsizing or loss of control. Proper ship design, including hull shape, ballast distribution, and rudder capacity, plays a critical role in managing these forces during turns. These forces include the circular motion force, and the wind force. The total force affecting the ship F_{total} when it is turning can be described by the following equation:

$$F_{\text{total}} = F_w \pm F_c \tag{3.1}$$

The notations F_w and F_c denote the wind force and the circular motion force, both in Newtons respectively.

The Froude number (F_r) is a dimensionless number that characterizes the flow regime of a fluid around a moving body, such as a ship or a boat. It is named after the British engineer William Froude, who introduced it in the 19th century [61]. The Froude number is particularly useful in naval architecture and fluid mechanics to predict the behavior of a vessel in water, particularly in terms of its speed, wave patterns, and resistance. It helps to determine whether the vessel is moving in a subcritical, critical, or supercritical flow regime. By monitoring the Froude number, it can be identified that when ship moves in a circular path, it leans inwards or outwards from the center of the circular path.

The Froude number is defined as the ratio of the ship's velocity to the speed of gravity waves in the water (see equation (3.2)).

$$F_r = \sqrt{\frac{V}{gL}}, \tag{3.2}$$

where $V, g,$ and L represent velocity of the ship, acceleration due to gravity, and the length of the waterline of the ship, respectively.

When the Froude number is less than or equal to 1, the lean is inward, when it is inversed lean is outward. As a result, when ships are turning, total force can either increase or decrease due to direction of the lean. If the Froude Number is less than 1, the ship leans inward. If the value is greater than 1, the ship leans outward. When F_r is 1, the vessel is moving at the critical speed, which is equal to the speed of wave propagation. The Froude number is used to estimate the speed at which a ship will operate efficiently. Ships are typically designed to operate at a Froude number less than 1, as it minimizes wave-making resistance and allows for more efficient fuel consumption. In model testing, the Froude number is used to scale model ship experiments to real ships. When testing ship models in a towing tank, the Froude number is kept the same for both the model and the full-scale ship to ensure that the hydrodynamic behavior is similar. The Froude number is directly related to the wave resistance experienced by the ship. At a Froude number around 0.5, the ship typically experiences low resistance, but as the Froude number increases, the wave-making resistance increases significantly. Ship designers use the Froude number to select the most suitable hull form. Vessels designed for high speeds often operate in the supercritical flow regime, where the Froude number is greater than 1. The Froude number also affects the stability and maneuverability of a vessel. For instance, ships operating at high speeds may experience slamming or hull deformation, where the Froude number plays a role in understanding these dynamic impacts. The Froude number is an essential dimensionless quantity in naval architecture and fluid mechanics, providing insights into the flow conditions around a vessel and its interaction with water. It helps in optimizing vessel design, predicting speed and resistance, and ensuring efficient operation in different hydrodynamic regimes. Understanding and applying the Froude number is crucial for the design, operation, and stability of ships, ensuring safety and minimizing fuel consumption while reducing wave resistance.

The heel angle refers to the tilting or leaning of the ship to the side, caused by external forces such as wind, waves, or centrifugal force during turns. In the context of a ship turning, the total heel angle is primarily influenced by the centrifugal force resulting from the turn, along with the ship's stability characteristics and its interaction with the water. The magnitude of the heel angle depends on several factors, including centrifugal force (turning moment), righting moment (restoring moment), stability of the ship, speed of the ship, radius of the turn, rudder and hydrodynamic forces, and external forces such as wind and waves. If the heel angle becomes too large, the ship's stability may be compromised, and the risk of capsizing increases. A large heel may reduce the effectiveness of the rudder, making the ship harder to maneuver. When a ship heels excessively, the righting arm (GZ) becomes smaller, which reduces the restoring moment. As a result, the ship may become more susceptible to further heeling or rolling, particularly in rough seas. Ships are designed with specific operating limits in terms of heel angles. Exceeding these limits may not only cause instability but also affect cargo safety, crew comfort, and operational performance.

Equation 3.3 describes the total heel angle θ_h affecting the ship when turning.

$$\theta_h = \theta_w + \theta_c \tag{3.3}$$

The notations θ_w and θ_c denote the wind heel angle and the circular motion heel angle, both in degrees respectively.

The wind force acting on a ship is a critical factor that influences the ship's maneuverability, stability, and heeling. This force is caused by the interaction between the wind and the ship's exposed surface area, typically the superstructure, deck, and sails. Wind forces are particularly important in shallow draft ships, offshore vessels, and during docking and undocking operations. The wind force acting on a ship is an important factor to consider for ensuring safety and stability, especially when operating in windy conditions. The magnitude of the wind force depends on the wind speed, the ship's exposed area, and the shape of the ship's superstructure. These forces can lead to heeling, course deviation, and increased resistance, which affect the ship's maneuverability and operational performance. Proper ship design, stability calculations, and operational planning are crucial to mitigating the effects of wind force on a ship. The wind force on the ship as illustrated in Figure 3.3 can be calculated with the help of a drag equation [62]. The drag equation is commonly used to calculate the wind force that acts on a ship, and it is derived from the general principles of fluid dynamics.

$$F_w = \frac{1}{2}\rho A C_w (V_w)^2 \sin^2 \alpha, \tag{3.4}$$

where ρ, A, C_w, V_w, and α denote the density of air (kg/m^3), the lateral area exposed to wind (m^2), the drag force coefficient (NA), the relative wind velocity (m/s), and the relative wind direction in degrees respectively. The drag force increases with the square of the wind speed (V_w^2). This means that even a small increase in wind speed results in a significantly larger drag force. The drag force also increases with the projected surface area A. A larger exposed surface area leads to higher wind drag. The drag coefficient (C_w) accounts for the shape and aerodynamic properties of the ship. A higher drag coefficient corresponds to a less streamlined shape, resulting in more drag. The wind force on a ship is significant in affecting the ship's maneuverability, stability, and

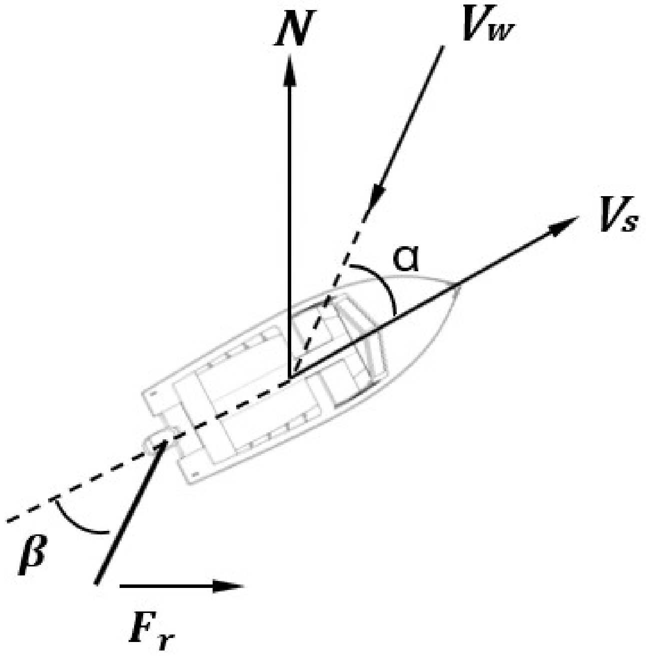


Figure 3.3: Wind Force on Ship

heeling, especially in high wind conditions. Understanding and calculating wind force is crucial for ship design, operational planning, and ensuring safety during operations, especially in harbors or high-wind areas.

Figure 3.4 illustrates the generation of moments due to the wind. The wind moment on a ship refers to the rotational effect caused by the wind force acting on the exposed surfaces of the ship. This moment generates a heeling effect or turning tendency, which can impact the ship's stability and maneuverability. The wind moment is essential for understanding how wind influences the ship's orientation and motion, especially when docking, undocking, or operating in high wind conditions. The wind moment on a ship is a crucial factor in assessing its stability and maneuverability in windy conditions. Understanding the wind moment is essential for ensuring safe operations, particularly in high-wind environments, where the ship may experience heeling, course deviation, or increased resistance.

The heeling moment refers to the rotational force that causes a ship to tilt or heel to one side. This moment is typically caused by external forces such as wind, waves, or the weight distribution of the cargo. In the case of wind and waves, the heeling moment is most commonly used to describe the effect of the wind force or the wave force on the ship's stability. The heeling moment caused by wind is a specific type of moment that results from the wind force acting on the exposed surfaces of the ship. This moment causes the ship to lean or heel to one side, depending on the direction of

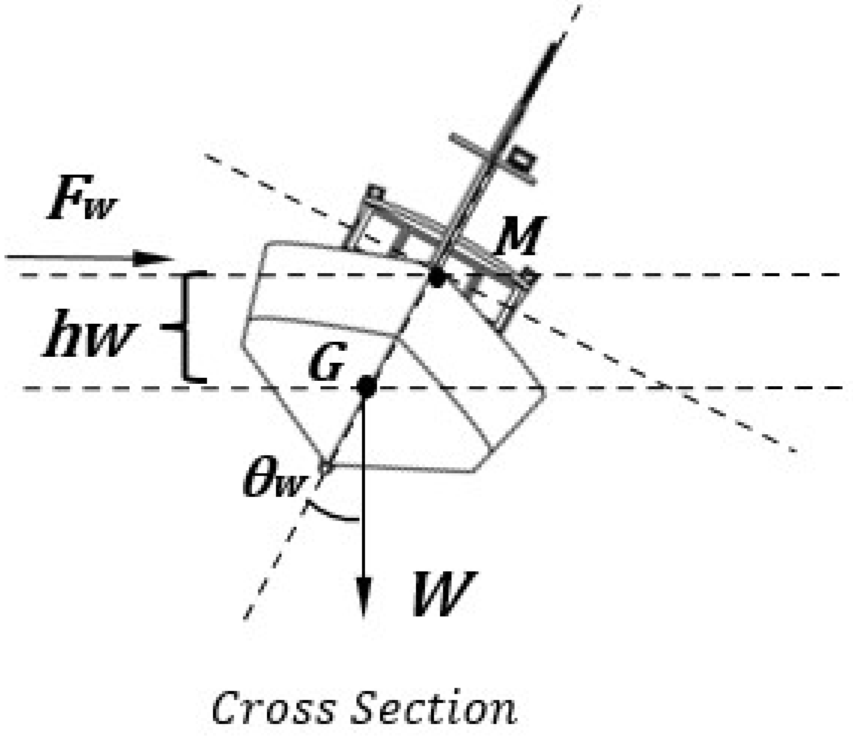


Figure 3.4: Moment generation due to wind

the wind relative to the ship's orientation. This moment causes a lateral tilt (or heel) in the direction of the applied wind force, with the magnitude of the tilt depending on the size of the wind force and the distance between the center of gravity and the wind force application point. Monitoring and controlling the heeling moment is crucial for ensuring the vessel remains within stable operational limits, especially in high-wind conditions, rough seas, or when cargo distribution is not optimal.

The wind moment and the heeling moment can be calculated using (3.5) and (3.6) respectively.

$$M_w = F_w \cdot h_w \tag{3.5}$$

$$M_h = W \cdot GM \sin\theta_w, \tag{3.6}$$

where M_w, F_w, h_w, M_h, W, GM, and θ_w denote the wind moment (Nm), the wind force (N), the height at which wind force acts (m), the heeling moment (Nm), the ship's weight (kg), the metacentric height from G (m), and the wind heel angle in degrees respectively.

The wind heel angle refers to the angle at which a ship tilts or heels due to the force exerted by the wind on the exposed surfaces of the ship. This angle is a measure of the lateral tilt caused by the wind moment and plays a critical role in assessing the ship's stability and maneuverability. The wind heel angle is especially important for ships with large superstructures or those navigating in regions with high wind conditions.

As the equilibrium wind moment will be equal to the heeling moment, the wind heel angle can be described by (3.7).

$$\theta_w = \sin^{-1}\left(\frac{h_w \cdot F_w}{GM \cdot W}\right). \tag{3.7}$$

In the context of ship stability and dynamics, circular motion forces play a significant role in determining how the ship responds to changes in direction and the forces involved in turning. The ship's design, particularly its center of gravity and righting arm, plays a significant role in determining how the ship behaves during circular motion. When the ship moves in a circular path, a circular motion force will be existed and it can be calculated as follows.

$$F_c = \frac{W \cdot (V_s)^2}{R}, \tag{3.8}$$

where F_c, V_s, and R denote the centrifugal force (N), the ship's velocity (ms), and the turning radius (m) respectively.

The turning radius of a ship is the radius of the circular path that the ship follows when it turns. It is a critical parameter in determining the maneuverability of the vessel. The turning radius depends on several factors, including the ship's speed, rudder angle, propulsion force, and the hydrodynamic characteristics of the hull. The turning radius increases with higher speed. At low speeds, a ship can turn more sharply, while at higher speeds, the ship requires a larger radius to make the same turn. The angle of the rudder controls the ship's turning ability. A larger rudder angle generally results in a sharper turn (smaller turning radius), but at extreme angles, the turning radius may increase again due to the limitations of the rudder's effectiveness at higher speeds. The shape and hydrodynamics of the hull affect how the water flow interacts with the ship's sides and rudder. Ships with a longer hull or more streamlined designs typically require a larger turning radius. The draught (vertical distance between the waterline and the bottom of the hull) can influence turning behavior. A deeper draught may result in less maneuverability, especially in shallow waters. The power of the ship's engines and the effectiveness of the propulsion system also play a role in how quickly and sharply a ship can turn. Ships with higher thrust can change direction more rapidly, reducing the turning radius. The trim (longitudinal angle of the ship) and heel (lateral tilt of the ship) can affect the ship's turning performance. Excessive heel can increase the turning radius. Understanding and calculating the turning radius helps in optimizing vessel design, navigation strategies, and safe operation in varying environmental conditions.

Turning radius R can be calculated according to (3.9).

$$R = \frac{\text{SOG}}{\text{ROT}} \tag{3.9}$$

The circular motion will be balanced by the rudder force and the calculated heeling angle due to the circular motion as shown in the equation (3.10).

$$\theta_c = \tan^{-1}\left(\frac{2W \cdot (V_s)^2 \cdot GM}{R^2 \cdot \rho_s \cdot A_r \cdot B} \cdot \csc\beta\right), \tag{3.10}$$

where ρ_s, A_r, β, θ_c, and B denote the density of sea water (kg/m^3), the rudder area (m^2), the steering angle (Degrees), the heel angle of steering (Degrees), and the ship's beam (m) respectively.

The total external force exerted on a ship will be determined as the sum of the vector forces of the wind force, the centrifugal force (due to circular motion) and other environmental forces. Assuming that other environmental forces are negligible, the total external force F_{total} can be calculated using (3.1), which simplifies the sum of the wind force and centrifugal force components.

The maximum external force acting on a ship is typically related to the largest forces the ship experiences from external sources, such as wind, waves, current, or the propulsive force. These forces can significantly impact the ship's maneuverability, stability, and structural integrity. Understanding these forces is important for ensuring the ship's safety and performance, particularly under extreme conditions. The determination of the maximum external force that a ship can withstand involves performing an inverse external force analysis. This analysis considers the range of heel angles within which the ship can maintain its stability. For each specific vessel model, the critical threshold of external force beyond which the ship's stability could be compromised can be calculated using this method.

The instantaneous wind force acting on a vessel is the force exerted by the wind at a given moment. It depends on various factors such as wind speed, wind direction, the shape of the ship's exposed area, and the drag coefficient. In parallel, the instantaneous force of the wind acting on the vessel is computed based on several parameters, including the ship's structural characteristics, the wind speed, and the wind direction, all of which are obtained through the ship's wind parameter monitoring system.

By comparing the threshold for critical external force with the instantaneous calculated wind force, this study determines the maximum allowable circular motion force that can be exerted on the ship without exceeding the stability limits. This difference is crucial for ensuring that the vessel can navigate safely under the given environmental conditions, preventing excessive heeling or capsizing by maintaining a safe steering angle and vessel speed as given in (3.11) and (3.12).

$$F_{\text{total}} - F_w = \frac{1}{2}\rho_s \cdot A_r \cdot (V_s)^2 \cdot \sin\beta \tag{3.11}$$

$$\Delta_f = \frac{1}{2}\rho_s \cdot A_r \cdot (V_s)^2 \cdot \sin\beta, \tag{3.12}$$

where Δ_f denotes the maximum steering force in Newtons. To ensure a safe steering process, (3.12) is used to create a data log of the maximum steering angles that a ship is permitted to have in order to guarantee a safe steering procedure. This procedure entails entering real- world numerical data into (3.12) for the ship's velocity, the density of seawater, and the rudder area. The computations are performed for different steering angles (0 to 35 degrees) and a variety of ship speeds (0 to 20 knots).

Important details about the maximum allowable steering angle at various speeds and situations are available in the data log. The ship's steering system is then transferred a corrected steering signal generated from this data. The utilized steering correction system makes sure that the steering process stays within safe operating parameters by following these estimated limits. This prevents excessive rudder forces that can jeopardize the ship's maneuverability and stability.

The microcontroller, empowered by this model, ensures that the ship maintains a safe and accurate course even under challenging environmental conditions. Through simulation, optimization, and real-time adaptation, mathematical modeling allows better decision-making, enhanced safety, and more reliable maneuvering in a variety of maritime scenarios.

CHAPTER 4

RESULTS

4.1 Introduction

The mathematical model developed in Chapter 3 establishes the relationship between a ship's steering angle and the circular motion force that the ship can safely endure. This chapter evaluates the model's accuracy through simulated scenarios, considering a range of steering angles (0 to 35 degrees) and various ship speeds (0 to 20 knots). The validation process involves generating detailed data logs for circular motion forces, wind forces, and total external forces acting on the vessel. The simulation software **Orca3D** is used for simulation of stability computations. **Orca3D** is a hydrodynamic analysis software that integrates with Rhinoceros (Rhino), a popular 3D CAD design platform, to provide tools for the design and analysis of ships, boats, and other marine vessels. Orca3D is widely used in the marine industry to perform hydrodynamic simulations, calculate stability, and assess various performance metrics of marine vessels.

The results are analyzed to demonstrate how the model predicts safe operational limits under different navigational scenarios. These findings provide critical insights into the interaction between external forces and steering dynamics, enhancing the ship's stability and safety.

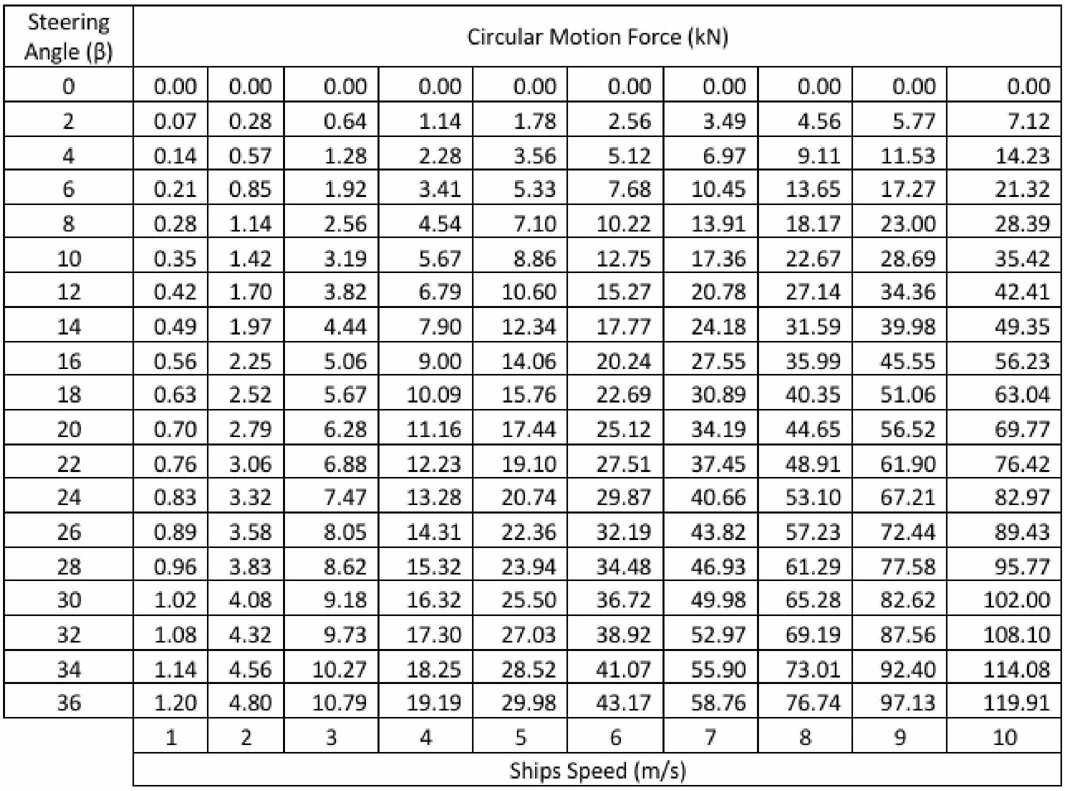
4.2 Circular Motion Force Analysis

Figure 4.1 presents the pre-calculated circular motion force for a specific ship model, characterized by a rudder area of $4m^2$. Results indicate higher speeds and steering angles lead to a significant increase in circular motion force, emphasizing the need for cautious steering at elevated speeds to avoid over-steering or heeling.

On the other hand, reduced speeds or steering angles mitigate the circular motion force, contributing to greater stability.

4.3 Wind Force Analysis

Figure 4.2 represents the wind force acting on a specific ship model with a windage area of $800m^2$. By analyzing this data, the wind force applied on the ship under different conditions can be determined. The combination of wind force and circular motion is considered as the total external force applied to the ship. By analyzing this data, the model's efficacy in predicting safe operational limits under different navigational scenarios is demonstrated. The results provide essential insights into how the ship's steering dynamics interact with external forces, ensuring that the vessel operates within



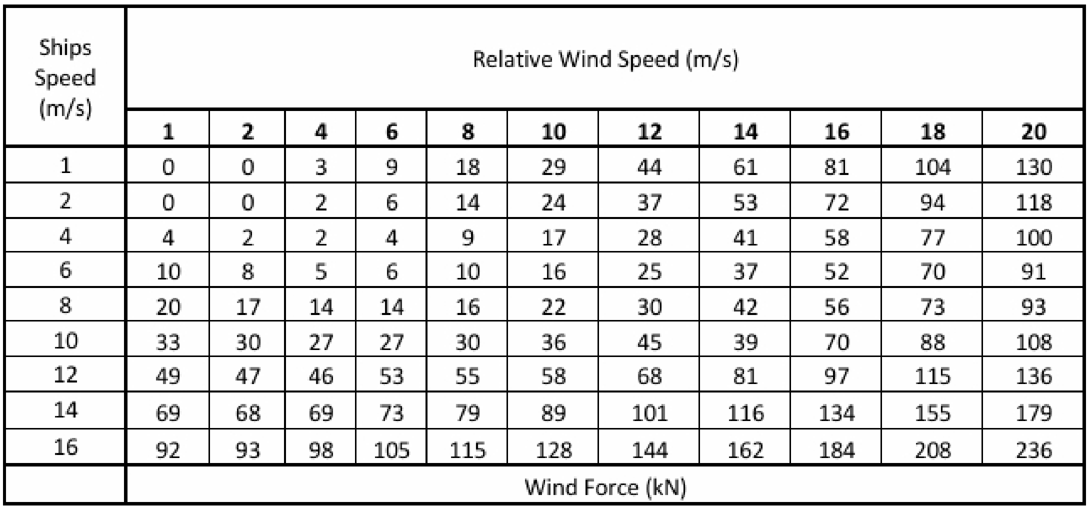
Steering Angle (β)	Circular Motion Force (kN)									
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.07	0.28	0.64	1.14	1.78	2.56	3.49	4.56	5.77	7.12
4	0.14	0.57	1.28	2.28	3.56	5.12	6.97	9.11	11.53	14.23
6	0.21	0.85	1.92	3.41	5.33	7.68	10.45	13.65	17.27	21.32
8	0.28	1.14	2.56	4.54	7.10	10.22	13.91	18.17	23.00	28.39
10	0.35	1.42	3.19	5.67	8.86	12.75	17.36	22.67	28.69	35.42
12	0.42	1.70	3.82	6.79	10.60	15.27	20.78	27.14	34.36	42.41
14	0.49	1.97	4.44	7.90	12.34	17.77	24.18	31.59	39.98	49.35
16	0.56	2.25	5.06	9.00	14.06	20.24	27.55	35.99	45.55	56.23
18	0.63	2.52	5.67	10.09	15.76	22.69	30.89	40.35	51.06	63.04
20	0.70	2.79	6.28	11.16	17.44	25.12	34.19	44.65	56.52	69.77
22	0.76	3.06	6.88	12.23	19.10	27.51	37.45	48.91	61.90	76.42
24	0.83	3.32	7.47	13.28	20.74	29.87	40.66	53.10	67.21	82.97
26	0.89	3.58	8.05	14.31	22.36	32.19	43.82	57.23	72.44	89.43
28	0.96	3.83	8.62	15.32	23.94	34.48	46.93	61.29	77.58	95.77
30	1.02	4.08	9.18	16.32	25.50	36.72	49.98	65.28	82.62	102.00
32	1.08	4.32	9.73	17.30	27.03	38.92	52.97	69.19	87.56	108.10
34	1.14	4.56	10.27	18.25	28.52	41.07	55.90	73.01	92.40	114.08
36	1.20	4.80	10.79	19.19	29.98	43.17	58.76	76.74	97.13	119.91
	1	2	3	4	5	6	7	8	9	10
	Ships Speed (m/s)									

Figure 4.1: Maximum allowable steering force chart

safe boundaries even under challenging environmental conditions. A key observation is stronger winds generate substantial forces that challenge the vessel's stability, especially when combined with higher steering angles. Moreover, Wind direction plays a critical role with forces varying significantly based on the relative angle between the wind and the ship's heading.

The model effectively incorporates these variables to calculate dynamic corrections to the steering angle.

The values which are derived for different conditions can be programmed into the microcontroller, based on the specific ship model. Hence, the microcontroller can continuously determine the maximum permissible steering angle at any given moment, considering the real-time external forces. The microcontroller's role extends to analyzing whether the forces exerted by the steering heel and the wind heel are in opposition or whether they are acting together. Based on this analysis, it will generate a corrective steering signal to the ship's existing steering system. This correction aims to adjust the steering angle remains within safe operational limits, thereby enhancing the ship's stability and safety under various environmental conditions. The mathematical model was tested by applying maximum permissible external force to the simulation software. Ship's weight, drag coefficient, windage area, metacentric height, wind speed



Ships Speed (m/s)	Relative Wind Speed (m/s)										
	1	**2**	**4**	**6**	**8**	**10**	**12**	**14**	**16**	**18**	**20**
1	0	0	3	9	18	29	44	61	81	104	130
2	0	0	2	6	14	24	37	53	72	94	118
4	4	2	2	4	9	17	28	41	58	77	100
6	10	8	5	6	10	16	25	37	52	70	91
8	20	17	14	14	16	22	30	42	56	73	93
10	33	30	27	27	30	36	45	39	70	88	108
12	49	47	46	53	55	58	68	81	97	115	136
14	69	68	69	73	79	89	101	116	134	155	179
16	92	93	98	105	115	128	144	162	184	208	236
	Wind Force (kN)										

Figure 4.2: Applied wind force calculation chart

and direction were given as the inputs. The heeling angle variation for a particular ship is shown in Figure 4.3.

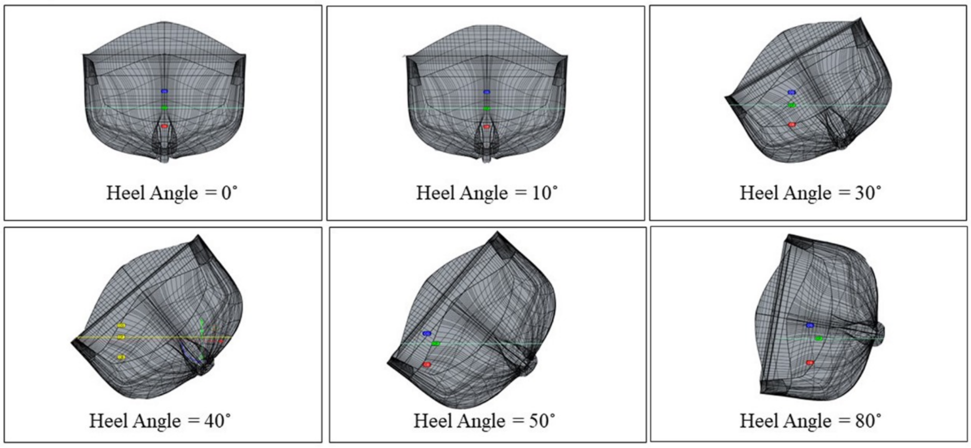


Figure 4.3: Heeling angle variation

4.4 Total External Force Analysis

The combination of wind force and circular motion force defines the total external force acting on the ship. By analyzing the derived data, the model demonstrates its efficacy in maintaining stability across various conditions.

When steering forces and wind forces act in opposition during ship maneuvering, they can create a natural stabilizing effect. Figures 4.4 and 4.5) represents variation of steering force and variation of wind force, respectively. The counteracting forces between the rudder (steering) and the wind provide a balance that can help the ship maneuver more smoothly and safely, particularly during turns. This interaction is important for safe navigation, as it allows the ship to adjust its course gradually and avoid sharp, destabilizing turns. Understanding and predicting how these forces interact are crucial for the effective operation of vessels in various wind conditions.

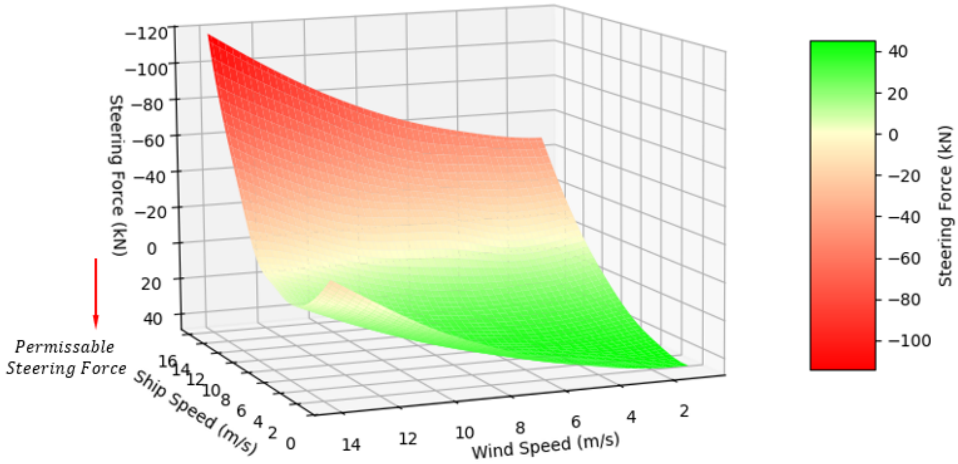


Figure 4.4: Variation of steering force with respect to ships speed and relative wind speed

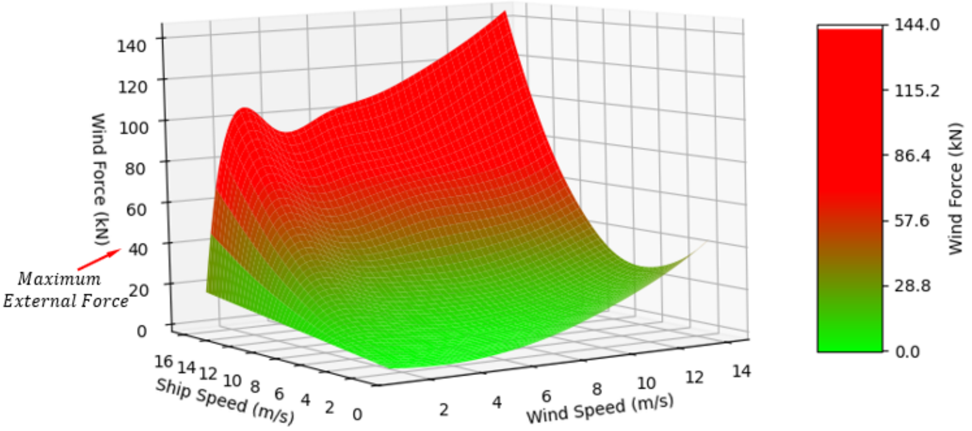


Figure 4.5: Variation of wind force with respect to ships speed and relative wind speed

When steering forces and wind forces act in the same direction, they can combine to enhance the ship's motion, but they also require careful management to prevent issues like over steering or capsizing. The ship's control systems whether they are automated or manually controlled adjust the rudder angle and other parameters to ensure the ship's movement remains within safe and efficient limits. By compensating for these aligned forces, the ship can maintain stable, controlled maneuvering, which is essential for safe navigation, especially under challenging wind conditions.

4.5 Validation of Heeling Angle Predictions

The external forces values which are derived for different conditions can be programmed into the microcontroller based on the specific ship model. Hence the microcontroller can continuously determine the maximum permissible steering angle at any given combination of wind force and circular motion force, considering the real time external forces. The microcontroller's role extends to analyzing whether the forces exerted by the steering heel and the wind heel are in opposition or whether they are acting together. Based on this analysis, it will generate a corrective steering signal to the ships' existing steering system. This correction aims to adjust the steering angle remains within safe operational limits, thereby enhancing the ship's stability and safety under various environmental conditions.

Figure 4.3 depicts the variation in heeling angles under different combinations of ship speed, wind speed, and steering angles. The results confirm that excessive heeling occurs at higher speeds and steering angles, especially when wind forces are aligned with the ship's motion. Stable operation is achievable within predefined thresholds, where the total external force remains within safe limits.

The mathematical model successfully predicts these scenarios, ensuring the ship's stability under varying environmental conditions.

4.6 System Testing and Hardware Validation

As part of the developed system for mitigating wind impact on ships, a hardware module was designed to monitor and display key operational parameters. Figure 4.6 illustrates the output of this module during testing, showcasing real-time data on steering command, rudder angle, wind speed, and the maximum steering angle. These values provide critical feedback for the system's operation under varying wind conditions. It generates accurate steering corrections based on real-time environmental inputs. Moreover, it displays critical parameters for operational monitoring and decision making.

This integration ensures seamless functionality between the mathematical model, hardware components, and existing ship systems.

4.7 Summary

The results validate the developed mathematical model and its integration with the microcontroller-based steering correction system. This model enhanced safety through dynamic adjustments to steering angles. Furthermore, it reduces risks of over-steering and excessive heeling, even under strong wind conditions. Practical feasibility of implementing the system in real-world maritime operations is another key observation of the results.

Figure 4.6: Display module output during testing

These findings underscore the potential of the system to improve maritime safety and operational efficiency.

CHAPTER 5

DISCUSSION

The results presented in Chapter 4 demonstrate the effectiveness of the microcontroller-based steering correction system in mitigating the challenges posed by strong wind conditions. This chapter discusses the implications of these findings, evaluates the system's strengths, and highlights areas for further improvement.

5.1 Analysis of Results

The mathematical model's performance, as validated through simulations and hardware testing, highlights its ability to accurately predict and mitigate external forces acting on the vessel. Key observations include:

1. **Circular Motion Force:** The results reveal a direct relationship between the circular motion force and variables such as ship speed and steering angle. Higher speeds and larger steering angles lead to exponentially increasing forces, emphasizing the importance of maintaining safe operational thresholds.

2. **Wind Force:** Wind force calculations demonstrate how varying wind speeds and directions significantly impact the ship's stability. The model effectively integrates these parameters to determine the corrective steering adjustments needed to counteract destabilizing forces.

3. **Total External Force:** By combining wind force and circular motion force, the model provides a comprehensive assessment of the total external force acting on the vessel. This capability ensures that the system generates appropriate corrective signals, maintaining the ship's stability across a wide range of environmental conditions.

5.2 System Performance

The integration of sensors, mathematical modeling, and real-time data processing ensures robust performance of the developed system. The microcontroller adjusts the steering angle dynamically, accounting for changes in wind conditions, ship speed, and heading. The system's ability to log critical parameters, such as maximum allowable steering angles, supports proactive decision-making and enhances operational safety.

5.3 Limitations and challenges

While the system demonstrates promising results, several limitations must be addressed:

The testing was conducted under controlled conditions, which may not fully capture the unpredictability of real-world maritime environments. Factors such as current, sudden wind gusts, and mechanical failures were not modeled, potentially affecting the system's reliability in extreme scenarios. The accuracy of the system relies heavily on sensor data. Inaccurate or delayed readings could lead to suboptimal steering corrections. Future iterations should incorporate redundancy mechanisms to mitigate sensor-related errors.

5.4 Future Work

To overcome the above mentioned limitations and enhance system performance, the following areas are recommended for future research and development:

1. **Field Testing:** Extensive sea trials can be conducted to validate the system's performance under diverse real world conditions. Moreover, feedback from maritime operators can be gathred to refine the system's functionality and usability.

2. **Enhanced Modeling:** We can expand the mathematical model to include additional environmental factors, such as wave dynamics and tidal currents, for greater accuracy. Further, machine learning techniques can be explored to improve predictive capabilities.

3. **Hardware Optimization:** We can integrate advanced sensors with higher precision and reliability to enhance data accuracy. Developing a user-friendly interface for real-time monitoring and control, leveraging Human-Machine Interface (HMI) technology, is another improvement in hardware optimization.

4. **System Integration:** We can investigate the potential for integrating the steering correction system with autonomous navigation systems for fully automated vessel operation.

5.5 Broader Implications

The system's development aligns with the growing emphasis on enhancing maritime safety and sustainability. By reducing the risk of accidents and minimizing operational inefficiencies, this technology contributes to lowering insurance premiums and operational costs for shipowners. Moreover, this system prevents capsizing and associated environmental hazards, such as oil spills. Supporting adherence to international maritime safety standards and regulations is another broader implication of the system.

The proposed system offers significant benefits for maritime operations by preventing over-steering and excessive heeling, the system reduces the risk of capsizing, ensuring the safety of both crew and cargo. The integration with existing steering mechanisms eliminates the need for costly hardware overhauls, making it a practical solution to retrofit older vessels. The modular design allows easy customization and implementation in various types and sizes of vessels.

CHAPTER 6

CONCLUSION

This research introduced a microcontroller-based system designed to enhance maritime safety by dynamically correcting a ship's steering angles in response to real-time wind conditions. By integrating advanced sensor technology, mathematical modeling, and real-time data processing, the system addresses critical challenges associated with over-steering and the risk of capsizing, particularly under adverse weather conditions.

6.1 Key Contributions

The study demonstrated several significant outcomes that contribute to maritime safety and operational efficiency:

1. **Steering Adjustments:** The developed system effectively monitors environmental and navigational parameters in real time, enabling precise corrections to the ship's steering angle to maintain stability and maneuverability under strong wind conditions.
2. **Mathematical Model Validation:** The mathematical model developed and validated in this study accurately predicts the forces acting on a vessel, including wind forces, circular motion forces, and their combined effects. This ensures safe and efficient operation within predefined stability limits.
3. **Scalability and Integration:** The system is designed to integrate seamlessly with existing ship steering mechanisms, making it cost-effective and adaptable across various vessel types and sizes.
4. **Improved Safety and Efficiency:** By mitigating risks associated with oversteering, the system enhances the safety of both crew and cargo while reducing the likelihood of accidents and operational disruptions.

6.2 Limitations and Future Work

While the system demonstrates strong potential, certain limitations warrant further exploration:

1. **Field Testing:** The simulations and controlled tests conducted in this study need to be extended to real-world sea trials to evaluate performance under varying environmental conditions, including current and sudden wind shifts.

2. **Advanced Sensor Integration:** Future iterations of the system could incorporate more advanced sensors, such as LiDAR or high-resolution anemometers, to enhance data accuracy and reliability.
3. **Autonomous Navigation Systems:** The system could be expanded to integrate with autonomous ship navigation technologies, paving the way for fully automated maritime operations.
4. **Machine Learning Enhancements:** Leveraging machine learning algorithms could improve the system's predictive capabilities, allowing it to adapt dynamically to previously unencountered conditions.

6.3 Conclusion

This research presents a robust and scalable solution for enhancing maritime safety by addressing the risks associated with strong wind conditions. In future, by combining cutting-edge technology with practical design, the system bridges a critical gap in modern maritime navigation. The system introduces an innovative solution to oversteering challenges, reducing the risk of accidents caused by strong winds. Minimizing accidents and ensuring smoother voyages contribute to reduced insurance costs, lower maintenance expenses, and improved profitability. Preventing incidents such as capsizing and oil spills helps protect marine ecosystems and aligns with global sustainability goals. It not only ensures safer voyages but also contributes to the efficiency and sustainability of the shipping industry. The findings underscore the system's potential to revolutionize maritime safety practices and its applicability across a wide range of vessels. As the maritime industry continues to evolve, this study serves as a foundational step toward developing more resilient and adaptive technologies to navigate the complexities of global trade and environmental challenges.

REFERENCES

[1] Sustainable development in shipping and ports. [Online]. Available: https://www.worldbank.org/en/topc/transport/brief/

[2] What are 7 types of cargo ships? [Online]. Available: sinay.ai/en/what-are-7-types-of-cargo-ships/

[3] Hanna. The vital role of the maritime industry in shipping. [Online]. Available: https://nmi.edu/the-vital-role-of-the-maritime-industry-in-shipping/

[4] B. J. Cudahy, *Box boats: How container ships changed the world.* Fordham Univ Press, 2007.

[5] H. Benford, "General cargo ship economics and design," Tech. Rep., 1968.

[6] J. Chen, W. Zhang, Z. Wan, S. Li, T. Huang, and Y. Fei, "Oil spills from global tankers: Status review and future governance," *Journal of cleaner production*, vol. 227, pp. 20–32, 2019.

[7] C. Comtoi and R. Lacoste, "Dry bulk shipping logistics," *Maritime Logistics: A Guide to Contemporary Shipping and Port Management*, p. 241, 2021.

[8] M. Kalajdžić and N. Momčilović, "A step toward the preliminary design of seagoing multi-purpose cargo vessels," *Brodogradnja: An International Journal of Naval Architecture and Ocean Engineering for Research and Development*, vol. 71, no. 2, pp. 75–89, 2020.

[9] B. Behdani, Y. Fan, and J. M. Bloemhof, "Cool chain and temperature-controlled transport: An overview of concepts, challenges, and technologies," *Sustainable food supply chains*, pp. 167–183, 2019.

[10] A. E. Branch and A. E. Branch, "Roll on/roll off (ro/ro) vessels and their features," *Economics of Shipping Practice and Management*, pp. 90–100, 1988.

[11] G. van de Merwe, S. Mallam, Ø. Engelhardtsen, and S. Nazir, "Exploring navigator roles and tasks in transitioning towards supervisory control of autonomous collision avoidance systems," in *Journal of Physics: Conference Series*, vol. 2311, no. 1. IOP Publishing, 2022, p. 012017.

[12] "Loses in focus," *Safety and Shipping Reviews 2024*, 2024.

[13] "Scientific bulletin 'mircea cel batran' naval academy," *Scientific Bulletin of Naval Academy*, vol. 22, pp. 2393–8956, 2019.

[14] C. Heij and S. Knapp, “Effect of wind strength and wave height on ship incident risk: Regional trends and seasonality,” *Transportation Research. Part D, Transport and Environment*, vol. 37, pp. 29–39, 2015.

[15] A. Maternová, M. Materna, A. Dávid, A. Török, and L. Švábová, “Human error analysis and fatality prediction in maritime accidents,” *Journal of Marine Science and Engineering*, vol. 11, no. 12, 2023. [Online]. Available: https://www.mdpi.com/2077-1312/11/12/2287

[16] Y. Zhou, W. Daamen, T. Vellinga, and S. Hoogendoorn, “Impacts of wind and current on ship behavior in ports and waterways: A quantitative analysis based on ais data,” *Ocean Engineering*, vol. 213, 2020.

[17] B. Barrass and C. D. Derrett, *Ship stability for masters and mates*. Elsevier, 2011.

[18] B. M. V. Ostretsov Genrikh Ehrazmovich and K. L. Mikhailovich, “Ship motion automatic control equipment.”

[19] N. D. Hai, N. N. Dam, and N. V. Giang, “Predicting the effects of the wind load direction to naval vessels resistance,” *International Journal of Transportation Engineering and Technology*, vol. 8, no. 2, pp. 18–24, 2019.

[20] M. Szymoński, “Some effects of wind on ship’s manoeuvrability,” *TransNav: International Journal on Marine Navigation and Safety of Sea Transportation*, vol. 13, no. 3, 2019.

[21] Q. Jing, K. Sasa, C. Chen, Y. Yin, H. Yasukawa, and D. Terada, “Analysis of ship maneuvering difficulties under severe weather based on onboard measurements and realistic simulation of ocean environment,” *Ocean engineering*, vol. 221, p. 108524, 2021.

[22] C.-H. Shih, P.-H. Huang, S. Yamamura, and C.-Y. Chen, “Design optimal control of ship maneuver patterns for collision avoidance: a review,” *Journal of Marine Science and Technology*, vol. 20, no. 2, p. 1, 2012.

[23] S. Sutulo and C. Guedes Soares, “Review on ship manoeuvrability criteria and standards,” *Journal of Marine Science and Engineering*, vol. 9, no. 8, p. 904, 2021.

[24] A. N. Madsen, M. V. Aarset, and O. A. Alsos, “Safe and efficient maneuvering of a maritime autonomous surface ship (mass) during encounters at sea: A novel approach,” *Maritime Transport Research*, vol. 3, p. 100077, 2022.

[25] L. P. Perera and C. G. Soares, “Weather routing and safe ship handling in the future of shipping,” *Ocean Engineering*, vol. 130, pp. 684–695, 2017.

[26] S. Thombre, Z. Zhao, H. Ramm-Schmidt, J. M. V. García, T. Malkamäki, S. Nikolskiy, T. Hammarberg, H. Nuortie, M. Z. H. Bhuiyan, S. Särkkä *et al.*, “Sensors and ai techniques for situational awareness in autonomous ships: A review,” *IEEE transactions on intelligent transportation systems*, vol. 23, no. 1, pp. 64–83, 2020.

[27] M. Harrer and P. Pfeffer, *Steering handbook.* Springer, 2017, vol. 163.

[28] A. F. Molland and S. R. Turnock, *Marine rudders and control surfaces: principles, data, design and applications.* Elsevier, 2011.

[29] H. Howard, “Hydraulic steering gears,” *Journal of the American Society for Naval Engineers*, vol. 34, no. 2, pp. 259–279, 1922.

[30] V. V. Kokotovic, J. Grabowski, V. Amin, and J. Lee, “Electro hydraulic power steering system,” *SAE transactions*, pp. 661–671, 1999.

[31] M. R. Martins and M. F. B. Natacci, “Reliability analysis of a rotary vane type steering gear system,” in *ISOPE International Ocean and Polar Engineering Conference.* ISOPE, 2008, pp. ISOPE–I.

[32] D. House, “Ship handling: Equipment,” in *Seamanship Techniques.* Routledge, 2018, pp. 665–709.

[33] Wikipedia, “Atmega328,” 2016, [Online; accessed 22-July-2024]. [Online]. Available: https://en.wikipedia.org/wiki/ATmega328

[34] S. Pindado, J. Cubas, and F. Sorribes-Palmer, “The cup anemometer, a fundamental meteorological instrument for the wind energy industry. research at the idr/upm institute,” *Sensors*, vol. 14, no. 11, pp. 21 418–21 452, 2014.

[35] F. Durst, A. Melling, and J. H. Whitelaw, “Principles and practice of laser-doppler anemometry,” *NASA STI/Recon Technical Report A*, vol. 76, p. 47019, 1976.

[36] J. D. Keys, “An acoustic anemometer.” 1948.

[37] E. Thornhill, A. Wall, S. McTavish, and R. Lee, “Ship anemometer bias management,” *Ocean Engineering*, vol. 216, p. 107843, 2020.

[38] V. M. Passaro, A. Cuccovillo, L. Vaiani, M. De Carlo, and C. E. Campanella, “Gyroscope technology and applications: A review in the industrial perspective,” *Sensors*, vol. 17, no. 10, p. 2284, 2017.

[39] S. Pace, G. Frost, I. Lachow, D. Frelinger, D. Fossum, D. Wassem, and M. Pinto, “The global positioning system,” *prepared for the Executive Office of the President, Office of Science and Technology Policy, Published by RAND, US*, 1995.

[40] J. Cannan and H. Hu, “Human-machine interaction (hmi): A survey,” *University of Essex*, vol. 27, pp. 46–64, 2011.

[41] C. W. De Silva, *Sensors and actuators: Engineering system instrumentation*. CRC press, 2015.

[42] Wikipedia, “National marine electronics association,” 2013, [Online; accessed 10-August-2024]. [Online]. Available: https://en.wikipedia.org/wiki/National_Marine_Electronics_Association

[43] R. B. Langley, “Nmea 0183: A gps receiver interface standard,” *GPS world*, vol. 6, no. 7, pp. 54–57, 1995.

[44] L. A. Luft, L. Anderson, and F. Cassidy, “Nmea 2000 a digital interface for the 21st century,” in *Proceedings of the 2002 National Technical Meeting of The Institute of Navigation*, 2002, pp. 796–807.

[45] Y. Sivkov, “Transformation of nmea ship network from sensor-based to information-based model,” in *2018 20th International Symposium on Electrical Apparatus and Technologies (SIELA)*. IEEE, 2018, pp. 1–4.

[46] L. I. Schiff, “Automatic steering of ships by proportional control,” *Transactions*, vol. 61, no. 1, 1949.

[47] D.-A. Pham and S.-H. Han, “Designing a ship autopilot system for operation in a disturbed environment using the adaptive neural fuzzy inference system,” *Journal of Marine Science and Engineering*, vol. 11, no. 7, p. 1262, 2023.

[48] M.-C. Fang, J.-H. Luo, and M.-L. Lee, “A nonlinear mathematical model for ship turning circle simulation in waves,” *Journal of ship research*, vol. 49, no. 02, pp. 69–79, 2005.

[49] S. Sutulo and C. Guedes Soares, “Mathematical models for simulation of manoeuvring performance of ships,” *Marine technology and engineering*, pp. 661–698, 2011.

[50] I. Lifanov, A. Setukha, Y. G. Tsvetinsky, and A. Zhelannikov, “Mathematical modelling and the numerical analysis of a nonstationary flow around the deck of a ship,” 1997.

[51] J. Vidic-Perunovic, “Influence of the gz calculation method on parametric roll prediction,” *Ocean Engineering*, vol. 38, no. 2-3, pp. 295–303, 2011.

[52] D. Perrault, “Correlations of gz curve parameters,” in *15 th International Ship Stability Workshop, ISSW*, 2016.

[53] D. R. Derrett and C. Barrass, “Ship stability for masters and mates,” *(No Title)*, 1990.

[54] G. Bulian, “Nonlinear parametric rolling in regular waves—a general procedure for the analytical approximation of the gz curve and its use in time domain simulations,” *Ocean Engineering*, vol. 32, no. 3-4, pp. 309–330, 2005.

[55] W. Wawrzyński and P. Krata, “Method for ship’s rolling period prediction with regard to non-linearity of gz curve,” *Journal of theoretical and applied mechanics*, vol. 54, no. 4, pp. 1329–1343, 2016.

[56] K. Ziha, “Displacement of a deflected ship hull,” *Marine technology and SNAME news*, vol. 39, no. 01, pp. 54–61, 2002.

[57] H. Martinez-Grueira, R. Asorey-Cacheda, A.-J. Garcia-Sanchez, and J. Garcia-Haro, “Understanding displacement of onboard contingents in navy amphibious ships,” *PloS one*, vol. 20, no. 1, p. e0316266, 2025.

[58] T. Mestl, K. T. Tallakstad, and R. Castberg, “Identifying and analyzing safety critical maneuvers from high resolution ais data,” *TransNav, International Journal on Marine Navigation and Safety od Sea Transportation*, vol. 10, no. 1, pp. 69–77, 2016.

[59] S. Brizzolara and E. Rizzuto, “Wind heeling moments on very large ships. some insights through cfd results,” in *Proceedings of the 9th International Conference on Stability of Ships and Ocean Vehicles, Rio de Janeiro, Brazil*, 2006, pp. 25–29.

[60] M. Ueno, Y. Yoshimura, Y. Tsukada, and H. Miyazaki, “Circular motion tests and uncertainty analysis for ship maneuverability,” *Journal of marine science and technology*, vol. 14, pp. 469–484, 2009.

[61] W. H. Hager and O. Castro-Orgaz, “William froude and the froude number,” *Journal of Hydraulic Engineering*, vol. 143, no. 4, p. 02516005, 2017.

[62] Calculating force due to wind. [Online]. Available: www.shiphandlingpro.com/calculating-wind-force