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Design and Manufacture Ballast Management System Model for Reduce Ship Rolling Motion

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The safety of maritime transportation is a critical aspect that must be addressed to ensure the well-being of ships and their crew. Frequent ship accidents highlight the need for improvements in the maritime transportation system. One of the causes of ship accidents is ship instability, leading to a loss of balance and even sinking. Ship stability is influenced by both internal and external factors, including human negligence in observing and addressing ship instability. This research aims to design and create a management ballast system model that can be operated automatically as a solution to reduce ship rolling motion. This system enables the ship to maintain balance using automatic side ballast tank management by utilizing two wing tanks on either side of the ship. The ballast management system will be equipped with an accurate ship roll angle detector, the Initial Measurement Unit sensor, a microcontroller, and a series of actuators, including relays as voltage control switches for the pump motor. This research involves simulation and testing/experiments at various angles, namely 5, 10, and 15 degrees. Simulations are conducted under conditions with and without the ballast management system, which is then confirmed through experiments under the same conditions. The expected outcome of this research is that the created ballast management system can be used to reduce ship rolling.

1. Introduction

Transportation safety is absolutely essential, and in this case, maritime transportation safety (ship safety) has several elements that must meet at least two relevant criteria. The first is seaworthiness and navigability. Seaworthiness involves meeting the 12 criteria set forth in Chapter IX of the International Safety Management (ISM) Code published by IMO in 2014 edition. Ship safety here encompasses the condition of the ship and its crew, meeting the requirements to maintain ship safety. These two criteria indicate that ship safety on land is the responsibility of the ship's owner, while ship safety on board is the responsibility of the ship's owner. The high number of ship accidents is an indication of the need for improvements in the maritime transportation system. Based on the National Transportation Safety Committee's (KNKT) report during the period from 2017 to 2021 in the waters of Indonesia. Accidents such as sinking, burning, exploding, collision, grounding, and others have led to conclusions related to contributing factors. Factors suspected of contributing to ship accidents include human error, technical issues, and weather [1]. One of the causes of accidents, whether offshore or in ports, is the lack of attention to ship stability, leading to an inability to maintain balance. At a certain angle of inclination, a ship may be unable to return to its original position and can even capsize and eventually sink. Ship stability is when ship is able to return to its original position after being affected by external forces such as waves, wind, or cargo handling [2]. Several factors influence ship stability, including internal factors originating from the ship itself, such as ship size, hull type, leakage due to grounding or collision, unbalanced cargo layout, and others. External factors are those external to the ship that affect its stability, such as weather conditions like wind, and stormy waves [3].

In most cases, accidents occur due to the negligence of the ship's crew in monitoring the ship's balance position, leading to delayed action. For example, in regaining balance using ballast tanks or ballasting, the ballast tank must be filled with water to increase the weight on one side to restore the ship to a balanced position. However, filling the tank requires precise timing, necessitating the use of a ship incline measuring device to ensure the ballast tank operates optimally [4]. In reality, recently there was a ferry accident in KM Satya Kencana III, which sank during cargo handling in West Waringin, Central Kalimantan. Was discovered that during cargo handling, the ship heeling due to one of the loaded trucks getting stuck. This caused the ship to heel, followed by the truck inside the ship with a full load being dragged to one side of the ship, causing a heel of more than 10°, water entering the ship, leading to its sinking. The high rate of ship accidents can be shown by data shown in Figure 1.

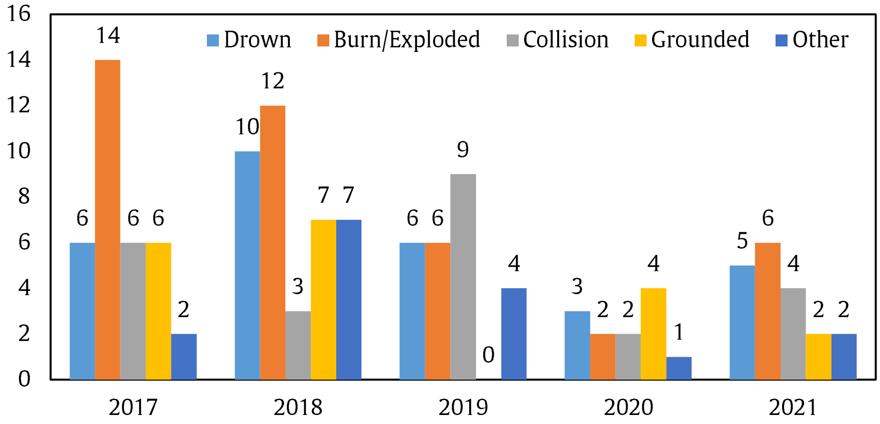


Figure 1. Ship accidents in Indonesia 2017-2021 [1]

Based on the data in Figure 1, it can be concluded that the safety system on ships is still low. Therefore, a system is needed to improve ship stability and prevent accidents due to ship instability [1] . One solution used is the management ballast system. This shift towards automation enhances industrial efficiency, making it more practical and environmentally friendly. It aligns with the broader trend of using technology to make maritime operations greener and more sustainable. The swift progress of technology has profoundly impacted various sectors, including the maritime industry, streamlining tasks, enhancing efficiency, and optimizing time utilization. This advancement has the potential to bring significant changes, improve work quality, and empower individuals to navigate its impact. In the maritime industry, the notable development of automatic ballast management systems exemplifies the transformative power of technology. An instance is the creation of automated control systems in human life, regulating quantities for specific values or ranges, crucial for control and regulation. On ships, a water ballast system exemplifies this control, adjusting water volume in tanks to stabilize the ship. A practical design aids maritime students in understanding automatic ballast water system operation, using simple tools in line with ballast water management principles, particularly for ship stability in unloaded vessels [5].

Efficient ballast systems are imperative for ensuring the swift response of a ship to its movements, a critical factor in guaranteeing the safety and comfort of the crew on board. The safety and well-being of the crew stand as paramount criteria that any ship must fulfill. To address these requirements, numerous research efforts have been undertaken to develop an automatic ballast control system tailored for ships. One notable application in this regard is the creation of an anti-heeling system for the ballast system designed specifically for supply vessels. This innovation showcases the ongoing endeavors in the maritime industry to enhance safety measures and optimize crew comfort through advanced ballast control systems [6]. Stability in the context of a vessel pertains to its capacity to revert to its initial position after experiencing a heel. It is defined as the ship's ability to return to a vertically upright position following a heel. During this movement, the volume of the vessel immersed in the water remains unaffected. The heel experienced by the ship in such conditions is referred to as equivolumetric inclinations [7].

The performance criterion for evaluating the effectiveness of the system could be measured in terms of either the time required to readjust the system parameters, such as the ship's position and orientation, to their reference values, or the amount of energy expended. In the context of ballast management system, the latter criterion is directly related to the quantity of water transferred within the ballast system. To optimize this process, the application of graph theory concepts to the equations of the characteristic mathematical model becomes crucial. This integration allows the development of a recursive algorithm designed to generate an optimal command sequence for the transport subsystem. The primary objective is to minimize transfers between tanks and the surrounding environment. In this way, the ballast management system plays a pivotal role in achieving optimal performance, ensuring efficient and stable adjustments of system parameters with minimal energy expenditure and water transfers [8].

Based on the issues discussed, research is conducted to design and construct a Management Ballast System Model on Ships to Reduce Ship Rolling Motion. In essence, this research aims to develop an automated ballast tank management system. This system aims to reduce the rolling motion of the ship and is designed to operate automatically according to the ship's conditions. Automation technology is becoming progressively prevalent across diverse industries, and the shipbuilding sector is no exception. Automation technologies have found their application within ships, with particular focus on crucial systems like the ballast system [7]. Efficient ballast systems should possess the capability to rapidly adapt to the ship's motions, a vital aspect ensuring the safety and well-being of the crew. Meeting the safety and comfort standards for the crew is among the fundamental requirements for any ship. Therefore, a system is needed to enhance ship stability and prevent accidents due to ship instability. One of the solutions used is the management ballast system [9].

The latest technology in the maritime sector has significantly advanced the automation of ship stability in accordance with IMO standards. State-of-the-art systems can effectively optimize ship stability automatically, responding to the dynamics of changing cargo and sea conditions, while considering operational efficiency and lower environmental impact. With the implementation of this technology, ships can maintain stability without sacrificing fuel efficiency, supporting maritime safety and global sustainability goals [10]. The specific objectives of this study can be delineated as follows: to understand the input requirements and component necessities for designing the ballast system management model, to establish the design of the ballast system management model on the ship, and to assess the comparison of outcomes before and after implementing the ballast system management on the ship model. This study can serve as a reference point for future research on ballast management systems. The advancements in technology applied to ballast management are expected to reduce the rolling motion and enhance the ship's stability.

2. Methods

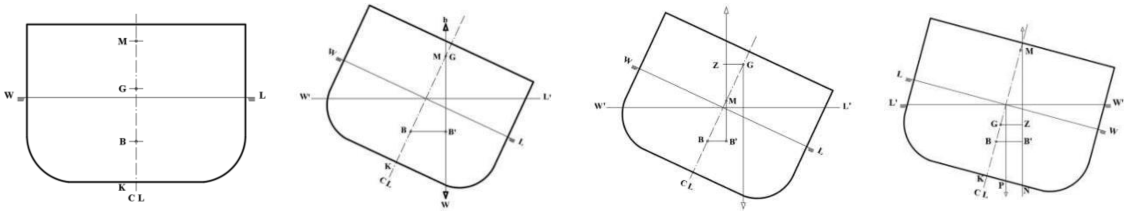
2.1. Management Ballast System

Ship stability is the ability of a ship to return to its original position after heeling due to external or internal influences such as wind disturbances, waves, uneven distribution of cargo within the ship, and others. In broad terms, ship stability is divided into two types, namely longitudinal stability, which is the ability of the ship to remain in a balanced position after experiencing longitudinal disturbances or forces on the ship's bow or stern. Meanwhile, transverse stability (rolling) is the ability of a ship to return to its original position after being disturbed from the outside in a transverse manner. Ship stability is closely related to the center of gravity (G) and the buoyant force or center of buoyancy (B). The center of gravity (CG) is the central point of the total weight of a ship. The ship's G point can be determined by assessing all weight distributions on the ship; the more cargo a ship carries, the higher the position of the G point [11].

$$KG_T = \frac{M}{W} \tag{1}$$

$$KB = T\left(\frac{s}{6} - \frac{1}{3}\frac{Cb}{Cw}\right) \tag{2}$$

Calculation of ship stability, several factors play a crucial role, including KGT (Vertical distance from the center of gravity of the ship to the waterline), M (Static moment about the waterline), W (Weight of cargo on the ship), T (Ship draft), Cw (Waterline coefficient), and Cb (Block coefficient). The most important point is the center of buoyancy (center of buoyancy), which is the center point of the vertical buoyant force exerted by the submerged part of the ship. The position of point B is not fixed as it can change with variations in the ship's draft.



a) Stable equilibrium

b) Neutral equilibrium

c) Unstable equilibrium

d) Righting moment

Figure 2. Ship equilibrium and its moment

As shown by Figure 2, the stability of a ship is divided into three conditions: stable equilibrium (positive stability), neutral equilibrium (neutral stability), and unstable equilibrium (negative stability). In a condition where point M is parallel to point G, the ship has good balance and can return upright after heeling. When the position of point G coincides with point M, the ship's righting moment has neutral stability equal to zero, or in other words, the ship cannot return to an upright position after heeling (it remains heeled at an angle). This happens because point G is too high and coincides with point M due to excessive cargo at the top of the ship. In a condition where point G is above point M, when the ship heels, it does not have the ability to return to an upright position, and the angle of heel continues to increase. Righting moment is the moment that restores a ship to its original position when it heels due to external or internal influences. This can be seen in Figure 2 above, which illustrates the righting moment of a ship [11]. The value of GZ represents the righting arm on a ship, which is crucial in determining a ship's static stability.

The calculation of static stability moments in ship stability involves several interconnected equations. The static stability moment, often denoted as W x GZ, is a critical parameter in understanding a ship's stability. The equation KN = KP + PN illustrates the relationship between the total righting arm (KN), the righting arm due to the weight (KP), and the righting arm generated by the buoyancy force (PN). Furthermore, PN is equal to GZ, which is the righting arm. This relationship can be expressed as Sin θ = KP / KG, where KP can be computed as KG multiplied by Sin θ. Additionally, the equation GZ = KN - KG * Sin θ demonstrates how to calculate the righting arm (GZ). It is determined as the difference between the total righting arm (KN) and the righting arm due to the weight (KG * Sin θ). The variable KG represents the distance between the ship's center of gravity (KG) and its metacenter (KM). This is a crucial factor in assessing stability. KG can be calculated as the difference between KM and GM, where GM signifies the distance between the metacenter and the center of gravity. These equations are fundamental in ship stability analysis, providing insights into a ship's ability to return to an upright position when subjected to external forces or inclinations. The studies before also mention that the static stability is closely related to the calculation of the GZ value. Requirements and recommendations for stability are closely related to discussions of the GZ curve in terms of preventing water from entering the ship. The GZ curve shows the relationship between the righting arm GZ divided into several variations of angles of inclination for a constant change in weight [12]. A ship's static stability curve contains the values of the righting arm (GZ) compared to the angle of inclination [13].

Management ballast on a ship is the process of controlling ballast water to regulate its distribution within ballast tanks, with the aim of maintaining the vessel's stability, trim, and draft. The fundamental principle behind this is Archimedes' principle, which states that a ship will experience buoyant force equal to the volume of fluid it displaces. When a ship is loaded with cargo, its weight can increase, causing an imbalance. To maintain stability, the ship's center of buoyancy and center of gravity must be carefully managed, and ballast water is added or discharged as needed. Ballasting inside tanks of a ship is an effective method for maintaining vessel stability by utilizing the principle of water displacement to reduce rolling motion. When a ship sails in the open sea with high waves or encounters strong winds, rolling can disrupt comfort and even jeopardize maritime safety. By using fixed ballast, the ship can control its inertia and enhance buoyancy. When the side tanks are filled with water, the ship gains increased mass, leading to higher buoyancy. This helps maintain vessel stability and provides resistance to motion changes, allowing the ship to better withstand disturbances and return to an upright position after experiencing disruptions [14].

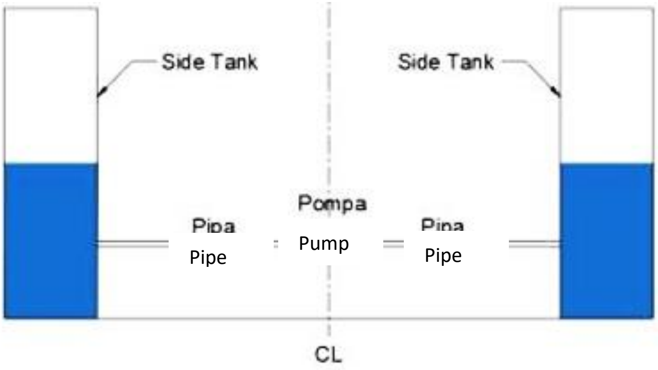


Figure 3. Model ballast side tank

Based on Figure 3, it can be observed that the ballast side tanks are connected by a series of pipes that function as fluid channels for transferring fluid from one side to the other. Additionally, the ballast side tanks are equipped with a pump motor, which serves as an actuator for transferring fluid from starboard to portside or vice versa. The use of fixed ballast in the side tanks not only enhances the ship's stability but also provides flexibility in adjusting the ship's weight as needed. When the ship carries a heavy load, the fixed ballast can be emptied to compensate for the additional load, thus maintaining stability. Conversely, when the ship sails with a light cargo, the side tanks can be filled with water to increase the ship's mass and optimize its stability. An automated control system based on measuring the ship's roll angle ensures that the filling or emptying of the side tanks is carried out as needed, allowing the ship to maintain a stable position [14].

$$M = F\ x\ l \tag{3}$$

$$F_\alpha = w_a \tag{4}$$

$$w_a = V\ x\ \rho \tag{5}$$

$$V\rho = (A\ x\ ta)\ x\ \rho \tag{6}$$

In the context of ship stability calculations, several variables and equations play a crucial role. One such equation involves the calculation of moments and forces acting on the starboard side of the ship. Here, M represents the moment of the load, Fa signifies the force experienced on the starboard side, l stands for the lever arm, wa represents the load on the starboard side, V is the volume of the tank, ρ represents the density of the fluid (usually water), A denotes the tank's cross-sectional area, and ta is the height of the fluid in the starboard tank.For the portside, it is assumed to be equivalent to the moment of load experienced on the starboard side. Consequently, the equation for the portside can be expressed as follows :

$$F_b = w_b \tag{7}$$

$$w_b = V\ x\ \rho \tag{8}$$

$$V\rho = A\ x\ t_b\ x\ \rho \tag{9}$$

To maintain the ship's stability after experiencing a list due to a shift in load, it is essential to determine the required change in fluid height (∆t) in one of the tanks. This change in fluid height is needed to counterbalance the moment of load obtained using the equations mentioned earlier. Additionally, it is crucial to calculate the force (Fb) experienced on the portside and consider the fluid height (ta) in the portside tank. By making these calculations, the ship's stability can be restored, ensuring it returns to an upright and stable position. As shown in Equation 10 -14, we need to calculate *ta* that represents the height of fluid on the starboard side and *tb* that represents the height of fluid on the portside to gain the value of the magnitude of fluid change (∆t).

$$t_a + t_b = 0.075 \tag{10}$$

$$t_b = 0.075 - t_a \tag{11}$$

$$(t_a - t_b) = 0.075 - 2t_a \tag{12}$$

$$(t_a - t_b) = 2t_a + 0.075 \tag{13}$$

$$\Delta t = 2ta - 0.075 \tag{14}$$

The use of a management ballast system as a method to reduce rolling motion on ships. The main objective of this research is to reduce ship instability during operations or cargo handling processes. In this study, the researcher employed a PID (Proportional-Integral-Derivative) control system to actively manage the ballast. This system is designed to automatically adjust the water volume within the management ballast, resulting in balancing forces that can reduce ship rolling motion. The research results demonstrate that the use of a management ballast system on ships successfully reduced rolling motion by 40% compared to previous conditions [15].

2.2. Design of Management Ballast System

The ballast management model is considered to have the same moment as the load moment resulting from initial testing of the ship model. This aims to return the ship to an upright position. Therefore, the main objective is to look for fluid changes on one side of the tank (∆t) [16]. The management ballast model was created with a capacity of 0.024 m^3. This capacity determination is based on the moment load calculations from the initial ship model testing data, where the moment of the management ballast model is considered equal to the moment of the test load. As a result, when water displacement is operated, it can return the ship to a stable position. The model-making process begins with designing the model, starting from 2-dimensional designs to 3-dimensional designs according to the predetermined size. The initial design of the model is depicted in Figure 4.

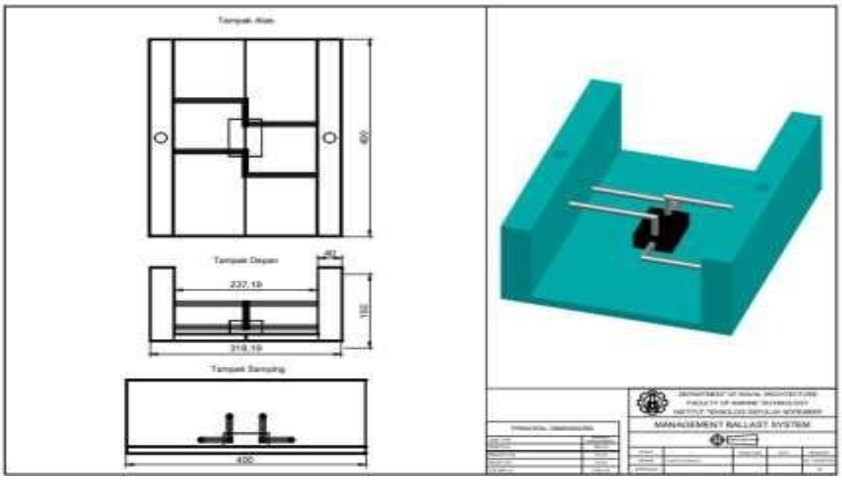


Figure 4. Initial design of ballast management model

Arduino Uno utilizes the ATmega328P microcontroller, capable of operating at a 5V DC working voltage with an acceptable input voltage range between 7 to 12V, but the maximum limit is 20V. This voltage capacity of Arduino Uno meets the requirements of the control system effectively. Additionally, Arduino Uno offers 14 digital I/O pins, crucial for controlling a series of actuators within the designed control system. Furthermore, Arduino Uno features 6 analog input pins, enabling the reception of data from various analog sensors. With a current capacity of up to 20 mA per I/O pin and 50 mA for the 3.3V pin, Arduino Uno can safely control various external devices [17].

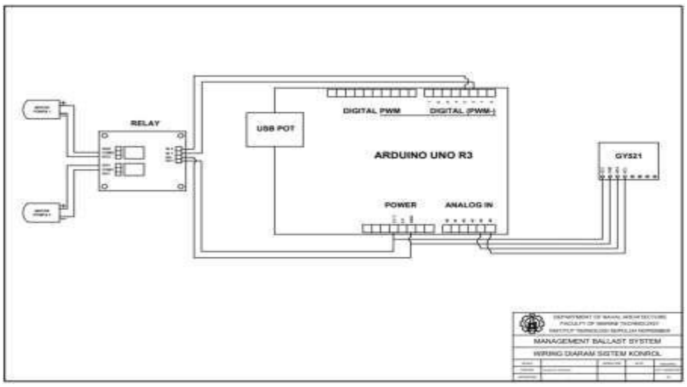


Figure 5. Control system wiring diagram

Figure 5 is the wiring diagram of the control system created, where the GY521 sensor and relay are connected to the Arduino Uno microcontroller. Motor pump 1 is connected to relay 1, and motor pump 2 is connected to relay 2. The GY521 sensor is equipped with 8 pins, but only 4 pins are utilized in this system: VCC, GND, SCL, and SDA. SCL and SDA pins serve as the data clock and sensor data reading pins, respectively. XCL and XDA pins are extra pins with the same functions as SCL and SDA, which can be connected to additional devices if necessary. ADC pins are unnecessary when using the Arduino Uno R3 microcontroller as it already comes equipped with ADC, and INT pins are unused due to the absence of an interrupt process. Additionally, this sensor operates within a 3-5V voltage range, which is sufficient for meeting the requirements of the designed control system.

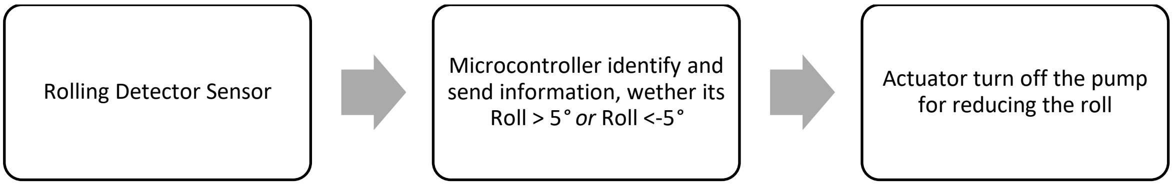


Figure 6. Control system flow

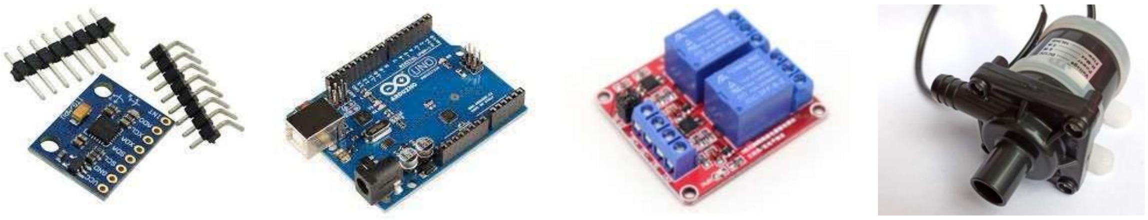
This program begins by reading the inclination sensor to determine the roll angle generated by the ship model. The sensor provides data on the ship's position in terms of roll motion to the microcontroller, which is responsible for processing the data received from the inclination sensor. Once the data is processed, the microcontroller sends this information to various interconnected components. One crucial component that receives data from the microcontroller is the actuator, which functions as a vital switch in controlling the pump motor. The processed data received from the microcontroller is used to govern the actuator's operation. The actuator acts as a relay or breaker of electrical current required to drive both the single and dual pump motors [18].

2.3. System and Programming Component

This automatic ballast stability test is carried out in two stages, namely when the ship is using the system and when the ship is in manual mode. The manual system one, the initial testing was conducted on a ship model with the aim of measuring the level of rolling and rolling period experienced by the model ship without any system to reduce roll motion. The data from this initial testing will be used as a reference in the creation of the Management Ballast model, which is intended to reduce the rolling motion of the ship. The testing was carried out in calm or static water conditions, without considering the influence of waves, and with a constant heavy load of 2.97 kg. The testing process involved three variations of heel angles 5°, 10°, and 15°. The recorded data from this testing will be used for comparison with the final results after the installation of the ballast management system on the ship model.

In this testing, two hardware components were utilized: Arduino Uno as the microcontroller board and the GY521 sensor as the angle detector for the model ship in degrees. For the disclaimer, Arduino IDE is an Integrated Development Environment used for programming and uploading code to an Arduino board, which functions as a microcontroller [19] . Programming done using the Arduino Software IDE is referred to as a "sketch" and is created in a text editor, saved with a specific file extension. The text editor in Arduino Software includes features like cutting, pasting, searching, and replacing, which make coding more convenient. Within the Arduino IDE software, there is a black-colored message box that displays statuses such as error messages, compilation progress, and program uploads [17]. One of Measurement Unit (IMU) module is the GY521 sensor, which utilizes the MPU-6050 chip from InvenSense. The MPU-6050 chip offers a 3-axis accelerometer (for measuring acceleration) and a 3-axis gyroscope (for balance sensing), providing a total of 6 degrees of freedom (DOF) for motion measurements. This module also includes a Digital Motion Processor (DMP) that processes raw data from these sensors [16]. In IMU modules like the GY521, raw data from the accelerometer and gyroscope is processed by the DMP within the MPU-6050. The DMP's role is to minimize potential errors in motion measurements. Data from these two sensors is then converted into quaternion data, which is a mathematical representation in four dimensions used to describe the orientation and rotation of objects. By combining the accelerometer and gyroscope within a single chip and utilizing the DMP for data processing, the MPU-6050 in the GY521 sensor offers a compact and efficient solution for motion and orientation measurements in various applications such as robotics, autonomous vehicles, and more [19].

Beside that, this experiment also using another tools such as relay and motor DC. A relay is an electronic component that acts as an electrical switch operated by an electric current. It operates based on electromagnetic field induction. When an electric current flows through a coiled wire known as a coil, a magnetic field forms around it. This magnetic field induces a ferromagnetic material, creating a magnetic force that attracts the moving part (armature) connected to the switch. Relays are commonly used to control equipment or circuits that require higher current or voltage using a smaller current or voltage. For example, they can control electrical equipment using a small current, such as 0.1 A/12V DC [20]. A 12V DC pump motor is designed to operate with a 12V DC voltage. It is used to drive a pump and generate the flow of fluids, such as water or fuel, in applications that require a fluid delivery system. The 12V DC pump motor is a suitable choice for applications where a 12V DC power source is available, and reliable fluid flow is needed. With its robust design and good performance, this pump motor can be used in various industrial and domestic applications [18].



a) Sensor GY521 b) Arduino uno R3 c) Relay 5V 2 channel d) Motor pump DC IV

Figure 7. Component of experiment

3. Results and Discussion

3.1. Ship Data

To conduct this research, a prototype ship is used as the research object. In this context, the chosen ship type is cargo. The ship is considered a suitable object for examining relevant aspects in this research. Therefore, this ship as a prototype is crucial for carrying out experiments and testing for the designed of ballast management system. The ship has complete and valid data, which can be used in the ship rolling modeling process in calm waters and the calculation of ballast tank moment management. The dimension of the ship are concluded in Table 1.

Table 1. Ship′ s dimension

Dimension	Notation	Size (m)
Length Overall	L_{OA}	0.221
Length Between Perpendicular	L_{BP}	1.970
Overall Wide	W	0.336
Height	H	0.195
Depth	D	0.043

Figure 8. Research ship prototype

3.2. Condition of Experiment

Experimental testing is conducted to compare two conditions on a ship model: without a ballast management system and with a ballast management system. The objective of testing without a ballast management system is to evaluate the ship model's ability to maintain stability after changes in cargo or weight distribution. Meanwhile, testing with a ballast management system aims to assess the effectiveness of this system in significantly reducing ship changes or tilting. Through this comparison, a deeper understanding is expected to be gained regarding the contribution of the ballast management system to ship stability in various cargo change scenarios.

3.3 Ship Model Testing without MBS

Testing was conducted to evaluate the ship model's ability to maintain its stability after changes in cargo or weight distribution. During the tests, the ship model's movements were observed and measured following changes in cargo, and then it was returned to its initial position to determine if it could regain its previous stability. The results of these tests provide information about the ship's stability and indicate the need for any necessary improvements or adjustments [21]. The initial testing focused on the ship model's rolling motion without the use of a management ballast system as a dampener. The testing involved three heel angle variations: 5°, 10°, and 15°. The testing procedure included the installation of an Arduino Uno and GY521 sensor as a roll motion detection system for the ship model. External forces were applied to induce rolling motion in the ship model. The data used for the initial ship model testing can be found in Table 2.

Table 2. First tasting ship on roll 10°

Name of test	Load	Unit	Load	Unit
Test Load Weight	2.900	kg	0.0029	m
Pendulum weight	0.020	kg		m
Length of pendulum string (measured from the ruler)	12.400	cm	0.124	m
Length of pendulum string (below the ruler)	1.500	cm	0.015	m
Distance from the center of the load to the CG (S)	14.500	cm	0.145	m
Distance from the center of the load to the CG (P)	14.500	cm	0.145	m
Pendulum displacement distance (S)	1.300	cm	0.013	m
Pendulum displacement distance (P)	1.650	cm	0.016	ton
Test load displacement distance	27.500	cm	0.275	m
Ship displacement			0.052	Ton
Test draft (T')			0.005	m

After the initial testing, the ship underwent a series of additional tests in which we measured the extent to which the ship rolled within a 15-second interval at three different angles: 5, 10, and 15 degrees. For this reason, the results of the natural heel of the ship for 15 seconds for several angle parameters as follows.

Table 3. Rolling motion response ship model at 5°, 10°, dan 15°

Time (s)	Roll on Ship without MBS		
	5°	10°	15°
1	-5.00	-10.00	-15.00
2	3.59	8.45	13.70
3	-2.40	-6.78	11.21
4	1.13	5.56	10.79
5	-1.11	-3.56	-8.95
6	0.91	2.41	6.04
7	-0.53	-1.43	6.04
8	0.41	0.82	2.82
9	-0.24	-0.53	-0.83
10	0.35	0.41	0.41
11	-0.28	-0.24	-0.31
12	0.21	0.31	0.31
13	-0.31	-0.28	-0.28
14	0.41	0.32	0.32
15	-0.37	-0.28	-0.25

3.4 Ship Model Testing with MBS

The Management Ballast model's moment calculation aims to determine the return moment. Input data comes from initial tests on the model ship with 5°, 10°, and 15° heel angles and a 2.97 kg regular load. The results help establish the Management Ballast model's dimensions to meet the required return moment after converting to tank volume. This involves designing and selecting materials based on prior moment load calculations to ensure the model can counterbalance the ship's applied load. The model will be constructed using 3 mm thick transparent acrylic material for structural suitability. Final ship model testing assesses its response to rolling at the three heel angles and evaluates the Management Ballast's roll reduction effectiveness with a 2.97 kg regular load. The pool testing involves components like Arduino Uno, GY521 sensor, relay, and pump motor, where the pump motor acts as an actuator upon commands from the GY521 sensor.

Figure 9. Rolling ship experiment using MBS

3.5 Comparison Result Between Ship Models Before and After Installing MBS

The final testing of the ship model involves using three different heel angle variations, just like in the initial testing, which are 5°, 10°, and 15°. The purpose of this final testing is to observe the rolling motion response of the ship model at each of these angle values after the installation of the management ballast system. Additionally, it aims to assess the response of the management ballast system model in returning the ship to an upright position after being subjected to a regular load of 2.97 kg for a predetermined duration. The experiment can be seen by the Figure 10.

Figure 10. Roll testing on ship prototype at 5°, 10°, and 15°

Figure 11 provides a visual representation of applying specific inclinations to the prototype ship equipped with the ballast management system (MBS). Through the conducted experiments, the outcomes indicate that the ship's response to the given inclinations, both before and after the installation of MBS, exhibits notable changes. Specifically, the results show a reduction in the roll motion after the implementation of MBS. This reduction in the roll motion can be attributed to the effectiveness of the ballast management system in stabilizing the ship in response to varying inclinations. The experiments demonstrate the significant impact of MBS on improving the ship's stability and reducing rolling motion. For the comparison of before and after result using the ballast tank management system, can be seen on Table 4.

Table 4. Comparison of rolling ship model result, before and after installation of MBS

Time (s)	**Comparison of Rolling Ship Model Result (ɵ°)**					
	5°		**10°**		**15°**	
	Manual	**MBS**	**Manual**	**MBS**	**Manual**	**MBS**
1	-5	-5	-10	-10	-15	-15
2	3.59	2.1	8.45	5.1	13.7	8.04
3	-2.4	-1.25	-6.78	-3.02	-11.21	-5.01
4	1.13	0.83	-3.56	1.57	10.79	4.1
5	-1.11	-0.31	2.41	-0.96	-8.95	-2.43
6	0.91	0.25	-1.43	0.48	6.04	1.34
7	-0.53	-0.29	0.82	-0.28	-4.72	-1.1
8	0.41	0.31	-0.53	0.32	2.82	0.35
9	-0.24	-0.22	0.41	-0.21	-0.83	-0.27
10	0.35	0.25	-0.24	-0.36	0.41	0.23
11	-0.28	-0.36	0.31	0.29	-0.31	-0.39
12	0.21	0.28	-0.28	-0.32	0.31	0.25
13	-0.31	-0.34	0.32	0.28	-0.28	-0.31
14	0.41	0.25	-0.28	-0.33	0.32	0.23
15	-0.37	-0.32	0.21	0.29	-0.25	-0.29

Table 5. Result of rolling ship response on 5° degree

Without MBS			**MBS**		
Parameter	Value	Unit	Parameter	Value	Unit
T	1.93	second	T	1.95	second
f	0.51	Hz	f	0.51	Hz
Rise time	-	-	Rise time	0.37	second
Peak time	-	-	Peak time	0.85	Second
Settling time	-	-	Settling time	2.90	second
Reduction	0.00	%	Reduction	41.50	%

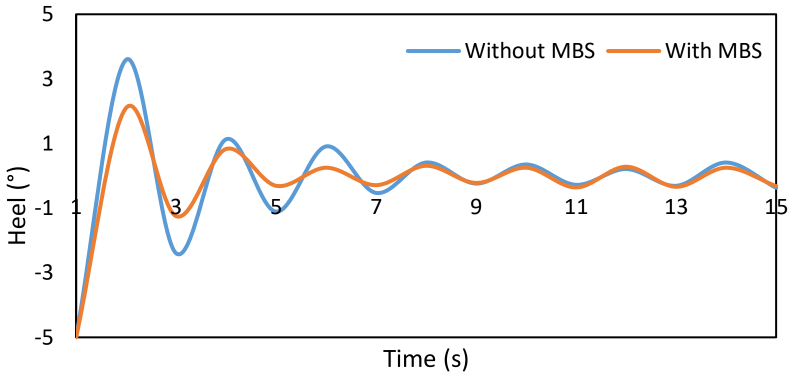


Figure 11. Comparison of rolling ship response on 5° degree

Based on Table 5, it is evident that after the installation of the ballast tank management system model, the rolling motion of the ship model yielded a lower roll compared to the rolling motion without the ballast tank management system model. The ship model achieved a final stable value of 0.83° with a period of 1.95 seconds and a frequency of 0.51 Hz. The transient response obtained includes a rise time of 0.37 seconds, a peak time of 0.85 seconds, and a settling time of 2.9 seconds. The use of the ballast tank management system model on the ship model resulted in a 41.5% reduction in rolling motion. Figure 12 is a graphic that shows the heel comparison between with and without installation of MBS.

Table 6. Result of rolling ship response on 10° degree

Without MBS			**MBS**		
Parameter	Value	Unit	Parameter	Value	Unit
T	1.94	second	T	1.93	second
f	0.51	Hz	f	0.51	Hz
Rise time	-	-	Rise time	0.48	second
Peak time	-	-	Peak time	1.10	Second
Settling time	-	-	Settling time	4.8	second
Reduction	0.00	%	Reduction	39.60	%

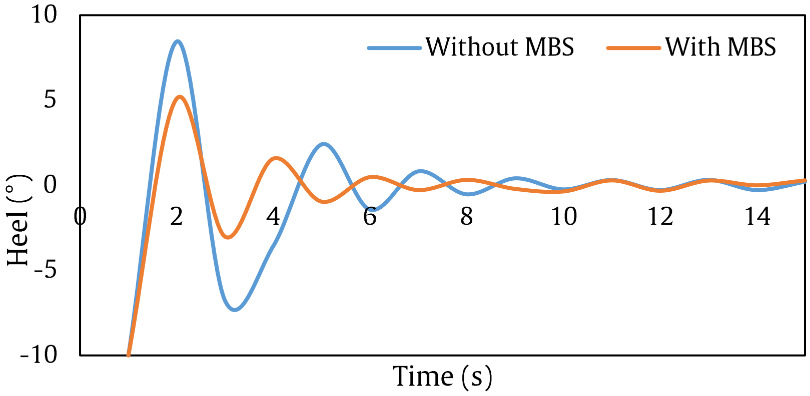


Figure 12. Comparison of rolling ship response on 10° degree

Based on Table 6, it can be observed that after the installation of the ballast tank management system model, the rolling motion of the ship model resulted in a lower roll compared to the ship model's rolling motion without the ballast tank management system model. The ship model achieved a final stable value of -0.96° with a period of 1.93 seconds and a frequency of 0.51 Hz. The transient response obtained includes a rise time of 0.48 seconds, a peak time of 1.1 seconds, and a settling time of 4.8 seconds. The use of the ballast tank management system model on the ship model resulted in a 39.6% reduction in rolling motion. The graphic that shown on Figure 13 also visualize how significant the changes of the result before and after.

Table 7. Result of rolling ship response on 15° degree

Without MBS			**MBS**		
Parameter	Value	Unit	Parameter	Value	Unit
T	1.94	s	T	1.92	second
f	0.51	Hz	f	0.51	Hz
Rise time	-	-	Rise time	0.65	s
Peak time	-	-	Peak time	1.2	s
Settling time	-	-	Settling time	7.0	s
Reduction	0.00	%	Reduction	41.3	%

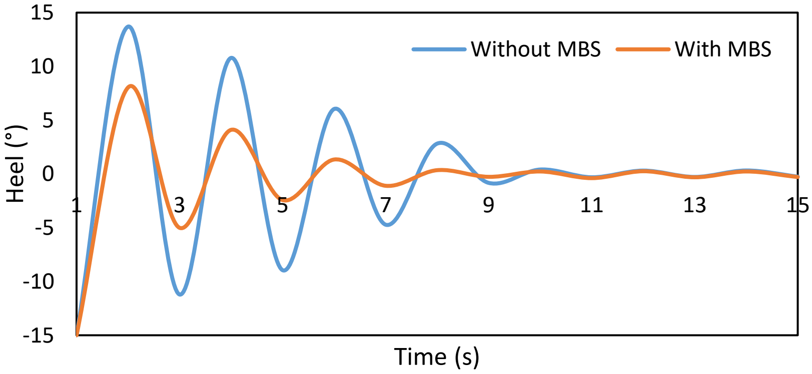


Figure 13. Comparison of rolling ship response on 15° degree

Based on Table 7, it can be observed that after the installation of the ballast tank management system model, the rolling motion of the ship model resulted in a lower roll compared to the ship model's rolling motion without the ballast tank management system model. The ship model achieved a final stable value of 0.35° with a period of 1.92 seconds and a frequency of 0.51 Hz. The transient response obtained includes a rise time of 0.65 seconds, a peak time of 1.2 seconds, and a settling time of 7.0 seconds. The use of the ballast tank management system model on the ship model resulted in a 41.3% reduction in rolling motion. And as seen from the graphic, it shows that how significant the changes before and after installation of the MBS (management ballast system).

4. Conclusion

After conducting experiments and research, we conclude the results of this Final Project as follows: The need to design and construct a ballast management system for a ship model involves the use of test data from a ship model without a ballast management system, an inertial measurement unit (IMU) sensor, a controller, and a set of actuators. The ballast management system model is constructed using 3mm thick acrylic material, with a control system consisting of an Arduino Uno microcontroller, a GY521 sensor to detect the roll angle of the ship, and a set of actuators including relays and a pump motor. The test results indicate that the ballast management system is capable of effectively reducing roll motion in the ship model, with varying levels of effectiveness for each angle variation. In testing with a 5° inclination angle, there was a 41.5% reduction in roll motion. Testing at a 10° inclination angle resulted in a 39.6% reduction in roll motion, while testing at a 15° inclination angle led to a 41.31% reduction in roll motion.

Future work in this research involves further development of an automatic ballast management system for cargo ships. The focus is on optimizing control algorithms and integrating advanced sensor technology, with the goal of enhancing the system's responsiveness to sea conditions and cargo loads, as well as enabling more effective adjustment of ballast distribution. This system also plays a crucial role in automatically reducing heel, making it essential for ship stability. Thus, the development of this system will not only improve the stability of cargo ships but also has the potential to shape a future maritime industry that is safer and more efficient.

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