GYRO MOMENT STABILIZER FOR 10M YACHTS

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Husam ABDULLAH KHALLEEFAH ALASWAD

ABSTRACT

M. Sc. Thesis

GYRO MOMENT STABILIZER FOR 10M YACHTS

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In the field of engineering design, gyroscopes have a long history of application due to their precession and rigidity. A spinning gyro disc rigidly maintains its orientation, which is an important characteristic of gyroscopes. This property is utilized in many sensor applications such as passive stabilization systems and navigation systems, which are used in torpedoes and ships. This research presents the study and design of a gyro moment stabilizer of a 10-meter yacht that stabilizes the yacht's rolling motion in 1-meter high sea waves. These waves force the yacht to roll. The force of waves creates torque that makes the yacht unsafe and uncomfortable.

To deal with this problem, a machine or a device is needed to make the yacht stable by producing a certain amount of torque that is equal to the torque produced by the sea waves. The research calculations are based on the Newton’s Second Law of Motion and Euler’s equations in the rolling motion of the yacht. By using Euler’s equations for a given or predicted angular acceleration of the yacht, the required torque is calculated with the help of moment of inertia of the yacht and the angular acceleration. Later, for the required torque, the angular momentum, mass moment inertia, and precession angular velocity of the gyro disc are used to find out the effectiveness of gyro specifications and design.

Key Words : Yacht, Gyro, Stabilizer, Angular momentum, Precession, Calculation, and Design.

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ÖZET

Yüksek Lisans Tezi

10 M LİK BİR YAT İÇİN BİR GYRO STABİZATÖRÜ TASARIMI

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Mühendislik tasarımında, jiroskop hassasiyet ve rijitlik nedeniyle uzun bir uygulama geçmişine sahiptir. Dönen bir jiroskop diski, jiroskopların önemli bir özelliği olan, uzayda yönünü düzgün bir şekilde korumaktadır. Bu özellik, pasif stabilizasyon sistemleri ve torpidolarda veya gemilerde kullanılan navigasyon sistemleri gibi birçok sensör uygulamasında kullanılır. Bu araştırma, yuvarlanma hareketini 1 metre yüksekliğindeki deniz dalgaları için dengelemek üzere 10 metrelik bir Yatın gyro-moment stabilizatörünün bir çalışmasını ve tasarımını sunmaktadır. Bu dalgalar, yatın emniyetsiz ve rahatsız edici olmasını sağlayan bir tork yaratacak şekilde, belli bir kuvvetle yatın yana yatmasına etki eder. Bu problemin üstesinden gelmek için, deniz dalgalarının ürettiğine eşit bir miktar tork üreterek yatın kararlı hale getirilmesi için bir makine veya cihaza ihtiyaç vardır. Araştırma hesaplamaları, Newton'un ikinci hareket kanunu ve Yatın dönüş hareketindeki Euler denklemlerine dayanmaktadır. Yatın belirli veya öngörülen bir açısal ivmesi için Euler denklemleri kullanılarak, gerekli tork yatın atalet momenti ve açısal ivmelenmesi yardımıyla hesaplanır. Daha sonra, gerekli tork için,yüksek hızla dönmekte olan gyro diskinin açısal momentumu, kütle ataletmomenti ve presessionaçısal hızı kullanılarak gyro'nun özellikleri ve tasarımı tayin edilmektedir.

Anahtar kelimeler: Yat, Gyro, Stabilizer, Açısal momentum, Presession, Hesaplama ve Tasarım.

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ABBREVIATIONS

CMG : Control Moment Gyrostabilizer

SYMBOLS

M : Total mass of equivalent triangle of the cross-sectional area of the yacht
L : Length of the yacht
μ : Equivalent mass density of the yacht
ω_r : Maximum rolling speed
$\propto$: Rolling angular acceleration
I_{gyro} : The moment of the inertia of gyro
ρ : Density of the gyro-disc
V : Disc volume

PART 1

INTRODUCTION

Controlling the motion of any yacht or ship is essential, and to accomplish this, the design of several marine vehicles makes it possible to operate them with sufficient economy and reliability. Making the marine vehicles follow the desired trajectory as closely as possible is the main control objective. In fact, that depends on the ship's velocity, position and acceleration. Generally, the low-frequency motion is suitable for a majority of operational conditions but moving in the desired trajectory might vary and it depends on motion and frequency of the waves.

Ship motion control problems include dynamic positioning and course keeping, which help controlling low-frequency motion of the ship. The wave-frequency motion is controlled for stabilizing the ships' sailing on the surface while for offshore structures, motion compensation is required. The operation can be performed if the wave limits are acceptable, under which, the desired trajectory can be set for different marine ship types and operations. Those limits can be imposed on the motion-derived responses, for example, motion-induced interruptions, motion sickness incidence, and besides, relative/absolute motions such as displacements, velocities and accelerations.

Some types of marine vessels need little wave-induced displacements for performing tasks or accomplishing missions, including drilling, pipe-laying, carrying aircrafts and weapon-handling. On the other hand, the wave accelerations may have negative effect on the crew performance and result in cargo damage. The seasickness can be produced due to long exposures to vertical accelerations that disturb the passenger comfort and the crew's effectiveness. Lateral accelerations affect the performance of the crew on the deck and cargo damage, and besides, they increase the time that the crew takes to accomplish their tasks.

In engineering design, the gyroscopes have a long history of application due to their precession and rigidity. A spinning gyroscope rigidly maintains its orientation, which is an important characteristic of gyroscopes. This property is utilized in many sensor applications such as passive stabilization systems and navigation systems, which are used in torpedoes or ships. The gyroscope can also be used as an actuator by utilizing the precession phenomenon. For this purpose, CMG systems use conservation of angular momentum to stabilize unstable bodies by functioning as an actuator applying the phenomenon of gyroscopic precession. When a flywheel spins with "ω" nalong the horizontal x-axis, if an external disturbance θ is applied along the y-axis (e.g. a bump in the road), and in case it has sufficient angular momentum, it will stay horizontal and begin to spin around along the z-axis. This spin along the z-axis is called precession.

The aim of this thesis is to study and design a control moment gyrostabilizer (CMG), which can be used in small-yacht applications, by focusing on specification of a 10M yachts, using mathematical calculations and designing proper dimensions that assure the maximum stabilizer performance. By using the designed control moment gyrostabilizer (CMG), the rolling motion of the yacht can be reduced to a point where one hardly feels it. This will bring some advantages to the yacht, for example, cooking in the stove will be safer, drinks can be placed on the table without the concern of spilling, and there will be many other advantages.

1.2. LITERATURE SURVEY

The researchers have examined the frameworks, dynamics and control of gyrostabilizers, which included a detailed review of these aspects on gyroscope stabilizer vehicle systems. This review first explains the historical development of gyroscopic systems, and then proceeds to define various system features, including gyroscope stabilizing vehicle applications, and provides an overview of system designs for land, marine and spacecraft. For generic gyroscopic systems, the equations of motion are derived by following approaches based on momentum (Newton-Euler) and energy (Lagrange) [1].

A general investigation survey of ship motion reduction devices has been conducted by Smith and Thomas, including gyro and other systems. The design of a fuzzy tuned

PID controller for Anti Rolling Gyro (ARG) stabilizer in ships has been presented by many researchers, and the authors demonstrated the development of a Gyro 375T Rolling Stabilizer for yachts utilizing the space-control technology. A wake-modifying device for a boat has been proposed by using multiple wings around the boat body. The ARG remained as a roll reduction device for vessels that utilize gyro torque stabilization even at zero speed. Recently, Mitsubishi Heavy Industries (MHI), Ltd., has developed and sold two sorts of ARGs, and has now developed a new framework, the ARG375T, which showed 50% increase in capacity as compared to the previous models. During the development of the ARG375T, marine trials were conducted in Japan and Europe to evaluate its anti-rolling performance, handling characteristics, safety envelope, and bench-testing to evaluate its performance and strength as key efficiency indicators [3-5].

Some scientists have presented benefits of fins in comparison with gyro, in addition to those, which are mentioned by Armstrong. The list of benefits included the possibility of wind heel control application that assures lower lifetime maintenance costs of gyros. The maintenance of fins might require a complete removal from the vessel in order to replace its part, for instance, the case of bearing replacement, which is not necessary in gyro [6]. The authors also stated other benefits, such as the lower weight and volume, faster response at zero-speed during anchoring, enhanced control performance, better tracking and navigation in sailing. “Gyros have to ‘spool up’ for 4560 minutes per gyro and can require sequential spooling to minimize the power practice,” while winding down can take four or five hours. There are a few drawbacks to fins that were mentioned by Mark Armstrong, including the need for through-hull protrusions (rudder or propeller) that are needed in gyros, as well as the longer roll periods of fins at zero-speed. Murphy and Olin (2009) stated the benefits of rotor stabilizers and mentioned DMS Holland as a pioneering company that produced them for yachts with a production range between 12 to 30 meters [7].

Researchers have discussed the use of a gyroscope in order to produce a torque that balances outside torque for monorail cars or two-wheeled automobiles. The utilization of the gyroscope in this case is as an actuator, and not as a sensor to the generated precession forces [8]. Studies have shown that the application of torque in the direction of the spin axis makes the gyro produce moment at one-third axis in an orthogonal direction to the torque and spin axis [9]. If the vessel tilts in the vertical direction, a precession-inducing torque applies to the gyro cage in order for the resulting gyroscopic reaction moment to return the vessel back to its normal position. The key idea of the gyro is the generation of a stabilizing moment by keeping the yacht relatively controlled during the motion.

Gyros were introduced for reducing roll motion of ships several years ago. The enhancements in mechanical design and digital control frameworks brought back the stabilizers into attention. The improvement of the performances of a twin-wheel gyro was achieved through nonlinear sliding mode-control method. The control strategy is robust and archives a stable framework to oppose wave perturbations. Comparisons between SM controllers and primary PD controllers are still a central area of research for assuring enhanced performance [10].

According to some scientists, the key gyro idea is to neutralize external torques applied to the vehicle through the counter torque produced from the two gyros placed on the vehicle. In this case, the gyros are utilized as actuators, not sensors[11]. The mechanism has been similarly described in the literature through the application of a continuous torque to rotate a gyroscope with a spinning flywheel. Then, the gyro processes this torque to generate moment, which is orthogonal to both the torque and the spinning axis. As the vessel leans from its upright position, the gyro is expected to generate sufficient moment reaction to bring the vessel back to its stabilized status [12].

Significant benefits have been observed both in terms of increasing efficiency and decreasing side-effects for all the boat types. Additionally, gyros are present in modern vessels, while old boat models had flat-fin stabilizers that did not achieve adequate roll reduction, in addition to many other issues, which include short natural roll periods and undesired motions that can be felt, such as sway and yaw in light vessels [13].
Operational circumstances have motivated specialists to the continuous pursuit of better movement control, which led to ocean trials of new propeller controlled devices in marine control structures [14]. In the late 1860s, the main test gyros were developed

with unattractive outcomes until the mid-1900s. In 1917, in cooperation with USS Henderson, a military transport dispatch utilized the innovation in a few boats that had two 25-ton units. In 1930, an Italian luxury ship utilized three vast units. With the goal to be more promptly accessible, the weights and the costs of structures were restrictive to development, and diverse types of adjustment were required. Outer blade adjustments turned out to be more popular, which utilized the speed of the vessel to make the motion adjustments. Through the vitality of its shape and ability to rotate the flywheel at high speed, the gyro is indeed useful for the vessel. Moreover, through the weight, width and RPM of the flywheel, the measurements such as torque, settling power and consequent rakish energy were determined [15].

The higher the yield of the moving torque is, the more hostile it will be so as to reinstate the balance of the vessel using a gyro. A few organizations have manufactured units to fit in any application in the game angling industry, in addition to manufacturing gyros for don angling pontoons. The quickest developing corporation in this domain is Ocean Guardian, which offers units that can fit each size of a game-angling vessel. Since there is no requirement for extra parts or crude water cooling, several Mitsubishi gyro models are independent and they can be fit in any type of vessel [16, 17].

1.3. RESEARCH AIMS AND OBJECTIVES

The aim of this thesis is to study and design a control moment gyrostabilizer (CMG), which can be used in small yachts. The gyro stabilizes the boat through the energy it creates by spinning a flywheel at high revolutions per minute. The subsequent angular momentum or stabilizing power is determined by weight, diameter and RPM of the flywheel, which are measured in Newton meters — a unit of torque. The output rating in Newton meters is the amount of power the unit is capable of generating to stabilize the boat. The more the output is, the more the anti-rolling torque will be generated by the gyro to stabilize the boat.

1.4. RESEARCH CONTRIBUTION

This research studies the design of gyro moment stabilizers in a yacht model: 10 meters length and 1-meteris the sea waves' height. The waves create an impact on the yacht through rolling with a specific force, which creates torque that makes the yacht unsafe and uncomfortable. In order to deal with this problem, there is a need for a machine or a device to reinstate the stability of the yacht by producing an equivalent force to counter the force of the sea waves. The research calculations are based on the Newton's Second Law of motion, while the force needed results from applying the mass with acceleration.

Using Newton's Second Law of motion, the force and acceleration can be calculated in order to calculate the moment of inertia, and then the torque. Later, all the calculations were utilized to determine the specifications of gyro.

1.5. RESEARCH METHODOLOGY

The CMG has a high-speed spinning flywheel supported by a gimbal. When the gimbal is rolled (i.e., angular velocity is applied to the gimbal), the flywheel generates a gyro force in the direction, which is perpendicular to the angular velocity. The output torque of the CMG and TARG is obtained from the cross product of the CMG angular momentum, and the gimbal angular velocity. The CMG uses this torque in the direction against the roll of the hull with net reduction in rolling.

Initially, a simple analysis was carried out to see how much the gyrostabilizer can theoretically help the stability. Gyroscopes can be very perplexing objects because they move in peculiar ways and even seem to defy gravity. These special properties make gyroscopes extremely important in everything from a simple bicycle to the advanced navigation system on the space shuttle. A typical airplane uses about a dozen gyroscopes in everything from a compass to the autopilot. The Russian Mir space station used 11 gyroscopes to maintain its orientation to the sun, and the Hubble Space Telescope has a batch of navigational gyros as well.

1.6. SCOPE OF WORK

The aim of this thesis is to study and design a control moment gyrostabilizer (CMG), which can be used in small yachts. The gyro stabilizes the boat through the energy it creates by spinning a flywheel at high revolutions per minute. This research studies and designs the machine or device of a gyro moment stabilizer of yacht: yacht span/length is 10 meters with certain specifications and the assumed maximum sea wave height is 1 meter. The research includes the following six chapters:

PART 1: The introduction that includes the background, a literature survey, some aims and objectives of this research, its expected contribution, the research methodology and the scope of work.

PART 2: A literature review has been presented, which includes an introduction about the essential ship motion control issues along with control systems, guidance, and the navigation system. Additionally, the introduction of gyrostabilizer throws light on the history of gyrostabilizers as well as their benefits and disadvantages. The chapter explains the justification of gyro moment utilization versus other frameworks. Moreover, the usage of gyrostabilizers, specifications and mass moment of inertia of an equilateral triangle in z- and x-axis has been provided. Fin stabilizers are introduced as well, with their advantages and disadvantages. This chapter provides an extensive understanding of marine gyrostabilizers with the mechanism and the torque of gyro-stabilizing, gyros' higher quality of comfort, the differences between fins and gyros, and placement of gyros on the vessel's centerline.

PART 3: The chapter provides more explanation of the ocean waves and kinematics of yacht motion, including the wave spectra and ocean waves, wave-period statistics and the maxima. Additionally, kinematics of yacht motion are provided, which focus on the body-fixed frame (b-frame; forward-starboard-down), geometric frame (g-frame, forward-starboard-up), n-frame (north-east-down), and hydrodynamic frame (h-frame; forward-starboard-down). Also, the vector notation and coordinates of yacht motion are clarified, which comprise seeking and maneuvering reference frames, maneuvering coordinates, sea-keeping coordinates, and angles along the z-axis.

PART 4: The chapter provides the results and their discussion, which includes the Newton’s Second Law of Motion, the calculation of the force and acceleration that help calculating the moment of inertia and the torque. In addition, the calculations of gyro specifications are also presented in this chapter.

PART 5: This chapter comprises the conclusions and recommendations of the research, which include future work recommendations as well.

Other parts: They include research references, appendices and a resume of the researcher, which have been provided at the end of the thesis.

PART 2

LITERATURE REVIEW

2.1. GYRO SYSTEMS AND CONTROL

2.1.1. The Motor Control Problem in Ships

A main issue pertaining to the ship motion control, which also helps reducing the wave-induced motion, is identifying the required behavior for a specific trajectory. This particular behavior can solve the issue of a ship's motion control. Figure 2.1 shows three interconnected systems, including the dynamic positioning, transit, diving for underwater vehicles, and assisted position mooring. The functions that these systems perform are following:

2.1.1.1. The Guidance System

Figure 2.1 shows the functions of the guidance system. The reference trajectory, such as acceleration, position, and velocity contribute to generate the desired performance. As far as the mission information is concerned, the power availability, weather, operator's decision, fleet operations, and the waypoint generator establish the desired waypoints. The waypoint management system updates the active waypoint for a ship based on its current position. Based on the reference model, the amount of available power, the active waypoint and the ship's actual position, a smooth feasible trajectory is generated by the reference computing algorithms.

2.1.1.2. The Control System

For reducing differences between the desired and actual trajectories, the information processing system generates the appropriate command for the actuators depending on the state of the ship. The controller has different operational modes, which depend on the operation type while a control system can combine the different modes: autopilot mode, dynamic positioning (DP) mode, and stabilizing roll and pitch mode. Additionally, the required control actions are accomplished in many ways because of over-actuation for some ships and operations. Thus, the same control action, or different combinations of control actions of actuator can yield different results. Based on some criteria optimization, the control system solves the “control allocation issue”.

2.1.1.3. The Navigation System

Reliable measurements are provided by this system through its operation. Furthermore, some basic functions are carried out by the navigation system, such as gathering data from several sensors and transforming the calculations into a reference frame, which is part of the guidance and control systems. Examples of this information are:

1. GPS,
2. Radar,
3. Speed log,
4. Gyros,
5. Compass,
6. Accelerometers, and
7. Signal quality checking equipment.

The control, navigation, and guidance mechanisms should be equipped with a redundancy and fault detection system, which is exhibited in Figure 2.1.These mechanisms allow reconfiguration of controls for minimizing the faults’ effect on safety as well as performance.

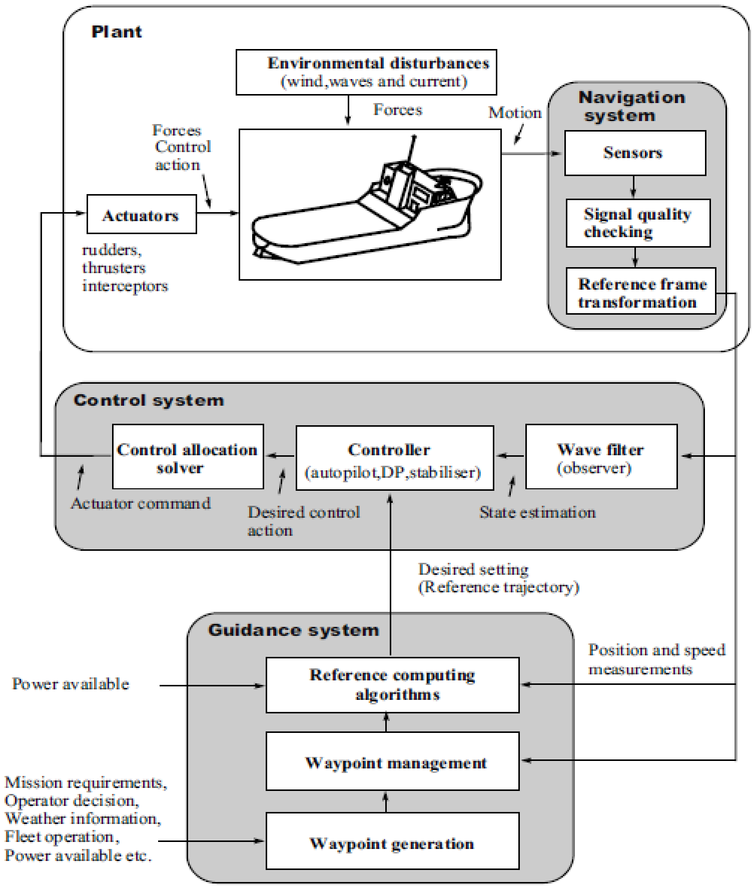


Figure 2.1. The fundamental ship motion control framework [18].

Progress in advanced technological aspects, the concentrated overall size of each unit and the decreased costs are the drivers behind the aggressive manufacturer approach towards the new product.

2.2. GYROSTABILIZER

In order to counteract the wave motion imposed on a yacht, the gyrostabilizer consists of a flywheel that spins at speeds of up to 10,700rpm and is in the range of up to 140 degrees. Gyroscopes are mainly PC-controlled. Starting from 2007, modern gyros have been in used in the recreational yachts [15, 19].

2.2.1. The History of Gyrostabilizer

Gyrostabilizer research began in 1888 with the patent application of a Benz automotive stabilization device was received. Then, technical interest began among inventors, who applied for the device's application patent. Schlick (1904) first proposed a patent for a marine stabilization device and it was first tested by White (1907) on the German torpedo battleship See-Bar. Moreover, Sperry (1908) tested the applicability of the active stabilizer while Fieux devised a stabilizer using dual gyros coupled to the gear[1, 20].

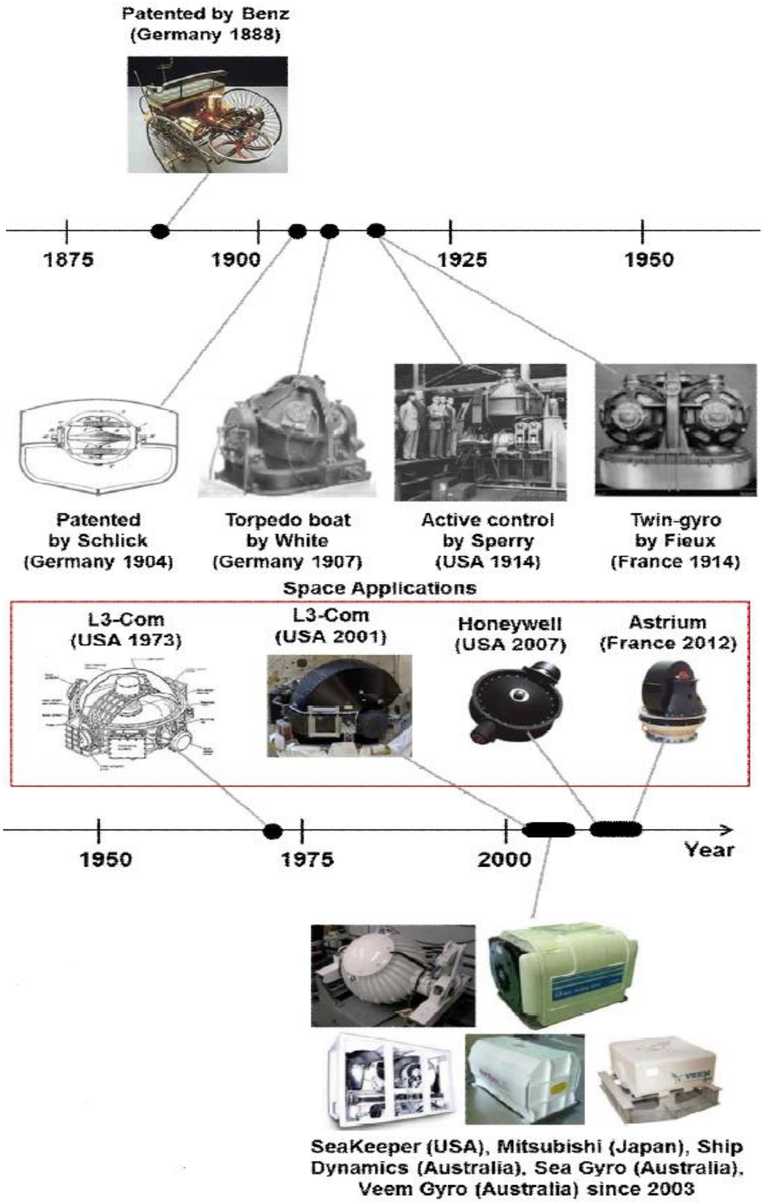


Figure 2.2. History of Gyro-stabilizer [20].

According to experts, a gyroscope has 3 axes, which are: The spin axis, input axis, and output axis. The spin axis is the axis, in which, the flywheel is spinning, and itis horizontal in the current research. The input axis is the axis, on which, inputs are applied. The principal input axis is the longitudinal axis of the boat since that is the axis, around which, the boat rolls. The principal output axis is the vertical axis, about which, the gyro rotates or processes in reaction to an input (Parsons, 1963).

When the boat rolls, it acts as an input to the gyro, which causes the gyro to generate rotation around its output axis; it is similar to the situation when spin axis rotates to align itself with the input axis[21]. This output rotation is depending on precession and in the current study, the gyro kept on rotating around the vertical axis. Dampers were coupled to the gyro’s precession axis to act as a brake, which controls the gyro’s precession rate. These dampers are set to match the roll characteristics of the vessel. The maximum output force applied to counteract the boat roll is governed through the following equation:

$$L = Iw \tag{2.1}$$

Active stabilization devices were applied to the USFW Worden in 1912, and then to civilian yachts as well; however, there has been no report of applications of gyro stabilizers since 1950. In 2000, Australia, the United States and Japan actively carried out development studies on commercial products and launched products that could be applied to civilian or military small and medium-sized vessels, as shown in Figure 2.3a,b.

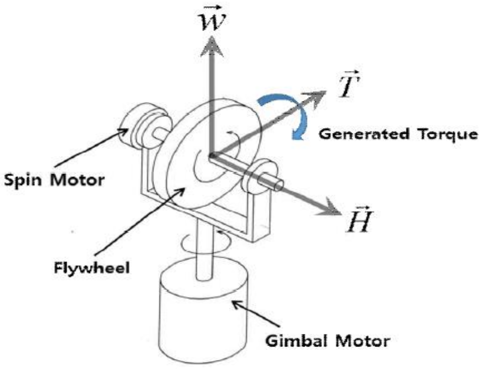


Figure 2.3a. Operational principle CMG [20].

Figure 2.4b. Operational principle CMG [20].

The gyrostabilizer basically consists of a flywheel, a spin motor and a gimbal. It is divided into a passive type and an active type according to the operating principle, as Figure 2.4 shows. In case of passive type, when the external force is provided as an input to the ship by using the gimbal, which is equipped with the braking mechanism and it can freely move, the gimbal rotates according to the principle of the gyro and stabilizes the shaking motion by using the generated repulsive force. In case of active type, the gimbal is actively driven with the controllable motor to generate the gyro torque to compensate the external force[20]. Figure 2.5 shows the common Gyro-stabilizer types, where (A) is Seakeeper, (B) Misaki engineering, (C) Ship dynamics, (D) Sea gyro, and (E) Veem.

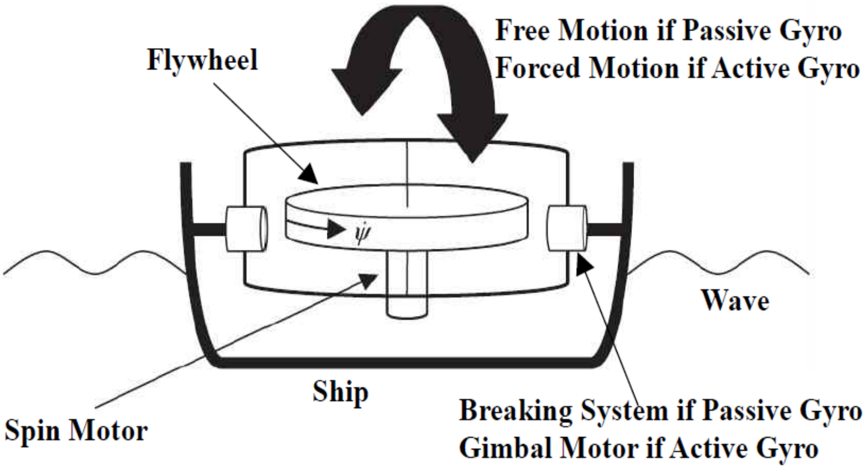


Figure 2.5. Ship Motion Control and the operational Principle of Gyro-stabilizer [20].

Figure 2.6. a), b), c), d), e) Common Gyro-stabilizer types [20].

The additional traditional designs consider various unit installations to meet the tonnage essentials and space imperatives of most watercrafts, and they can similarly be mounted off the centerline to fit a variety of usages. To keep the yacht stable and making the guests feel incredible, both Gyro and Fin stabilizers are reasonable devices. Based on the yacht format and its proposed usage, the decision between the two devices can be made. The counseling performed by the maker's specialists determines the choice, which can differ from a company to another according to their preferences.

The gyrostabilizers are available in direct, drive, and indicating forms as demonstrated through their undertaking control. The offsetting properties of a free spinner are utilized in gyrostabilizers [17]. Moreover, in order to balance out the identification parts of the control structures, the move dampers on ships, which act as stabilizers for monorail automobile, are utilized through gyrostabilizers. The radio wire and the facilitator, in addition to the chamber and rotor, are mounted in the outer gimbal ring of the gyrostabilizer for settlement [22]. From a given direction OA, the organizer creates signals with respect to the deviation of the receiving wire's pivot.
The intensifier converters and the moment transducers work with the cure framework. The accepting wire hub gives direction, which is called gyroscopic servomechanisms [22, 23].

Powered gyrostabilizers are electromechanical devices with exceptional motors for overcoming the disturbing actions and acting like whirligigs. For settling solitary instruments and contraptions, gyrostabilizers are used on planes, vessels, and different ships. The rule of gyroscopic-controlled adjustment is a part of a couple of types of directional whirligigs: mix contraptions and vertical tomahawks that are called gyro azimuth horizons. For each edge of alteration of powered gyrostabilizers, there may be two or three tomahawks [23].

Through actuators, the ship alters the movement through several methods for adjusting the control frameworks, such as exist vague parameters and questionable external disturbances [24]. As indicated by the ship’s movement, the weaknesses are identified through control inputs and fiery structural control variables in order to generate movement modifications, which is possible through opposition mechanisms [24, 25]. Diversions are plotted in an arranged framework to facilitate guaranteed actions through disturbances and vulnerabilities [25].

The chamber, the rotor, and the edge work as the external gimbal ring. The point sensor is mounted on the pivot of processional O_η, the enhancer, and the balancing out engine, which are applicable to the axis of adjustment. The O_η minutes, which make up for the outer aggravating minutes, follow up on the edge. The pendulum corrector and minute transducer are components of the gyrostabilizer redress structure. The chamber starts to perform in agreement with its gyroscopic properties with respect to the axis O_x, after the activation of an outer irritating minute M that tends to turn the body about the pivot O_η.

In this case, a gyroscopic minute Mg, which contradicts the minute M, emerges through a specific edge β.The endless supply of the chamber about the pivot O_x with respect to the hub O_η and the adjustment minute M_s, is inverse to the minute M. The edge sensor activates the concerned balancing-out engine. As the aftereffect of this, the chamber begins to process the other way and grinds to a halt at a consistent estimation of M, so that $M_s + M = 0$. In this way, in a controlled gyrostabilizer, the gyrator carries out the adjustment just at the underlying minute. Through the balancing out engine, adjustment is accomplished. Utilizing a gyrator of direct size and weight makes it possible to balance out the remarkable masses. Two-spinner gyrostabilizers have been utilized for this purpose, which are different because they have a few points of interest [26-28].

With respect to the plane of the horizon, the combination of two uniaxial gyrostabilizers forms a biaxial gyrostabilizer that offsets a phase. A mix of three uniaxial gyrostabilizers yields a tri-axle-controlled gyrostabilizer, which consists of a directional whirligig and a vertical gyroscope gyro horizon. For spatial alteration of stages, the tri-axle gyrostabilizer is in use. Settle-marker gyrostabilizers are customized control frameworks, in which, the gyroscopic devices are mounted. They are recognizing or expert segments that choose the inquiry position and control the servomechanisms. Nevertheless, the alteration of the stage is performed through methods for servomechanisms. Using whirligigs, rate gyroscopes, or free static spinners is possible through spinners [28].

2.2.2. Benefits of a Gyro Stabilizer

Gyrostabilizers are beneficial devices; their benefits are listed, as follows:

1. In addition to decreasing the roll, the gyrostabilizer greatly decreases the pitch [15].
2. A gyrostabilizer can be applied from 30 to over 100 degrees.
3. The gyrostabilizer works at the anchor and the dock.
4. It helps cruising at high speeds.
5. While stabilizing, no external devices are needed to reduce the drag [23, 29].
6. From a large unit to multiple smaller ones, the gyrostabilizer comes in many diverse sizes and works in multiple configurations depending on a yacht’s layout [30].
7. Gyrostabilizers do not require much power: From 3kW in startup mode, to 1-2kW while operating.

2.2.3. Disadvantages of a Gyro Stabilizer

1. To reach their operational speed, the gyros can take 30-45 minutes to warm up [31].
2. The real challenge is to find the space because a gyro takes considerable space inside the yacht.
3. If not mounted properly in the right area; it can cause considerable damage. For that reason, the gyros need to be mounted to the stringers of the yacht because high levels of force and stress are required [19, 32].
4. The manufacturer knows how to install a properly stringer reinforcement in a new yacht [33, 34].
5. In a 60ft yacht, a rig of 2 smaller gyros could cost up to $250,000, so it is a very advanced framework but it is not cheap [16, 25].

2.2.4. Why Gyro Moment is better than the Other Frameworks

1. Easy to operate with flip of a switch to turn it on.

2. Nothing protrudes from the hull, so it is resistance-free.
3. Operative at trolling and zero speeds.
4. Gyro is simple with no high-pressure hydraulic lines or pumps.
5. Can be installed anywhere where there is sufficient strength.
6. No heat exchangers to leak and there are no fresh or raw water pumps.
7. Gyro works at normal pressure; so, there is no vacuum chamber.
8. Gyro is safe because it has no exposed moving parts, and it requires engine room setting.
9. It is practically maintenance-free besides being a time-tested, proven, and dependable design.
10. The gyro is the leader in the marine gyro stabilization field. It is useful even after more than 25 years of service.
11. The gyro operates in extreme conditions at sea, if it is safely installed inside the boat.

2.2.5. The usage of Gyro Stabilizer

1. To determine an object’s position in ships and airplanes for measuring the three angles [35].
2. It is used in vertical-powered gyroscopes [16, 17].
3. In the inertial navigation frameworks [22].
4. Using the sensing elements and reacting to angular velocities, or to angles of deviation [23].
5. In the inertial navigation frameworks, on ships and in aircrafts [24].
6. It exerts torque opposite to the roll, which decreases the roll of a boat [26].

2.2.6. Mass Moment of Inertia of an Equilateral Triangle

For the calculation of the approximate mass moment of the inertia of a small yacht, an upside-down triangle model is used, as shown in Figure 2.6. An equilateral triangular prism is used for the determination of the moments of inertia of a solid body. The model is utilized by assuming most of the symmetrical approximation of the vessel and using the parallel axis theorem to deal with the challenge of problem simplification.

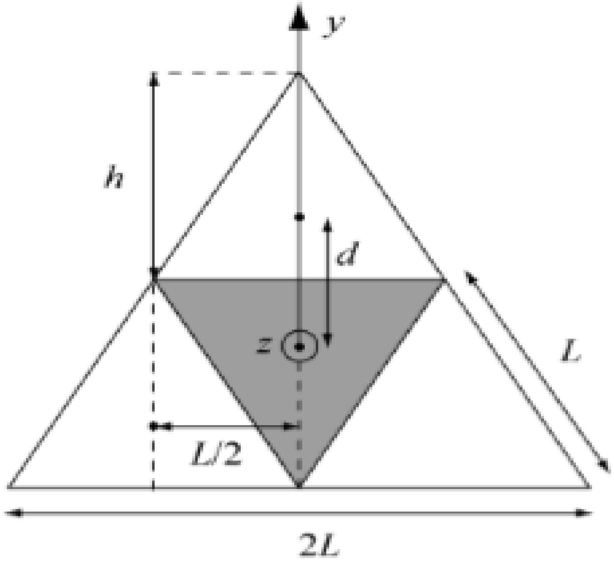


Figure 2.7. An equilateral triangular prism [26].

2.2.6.1. The Z-axis

The z-axis goes through the center of mass of the triangle of interest, as shown in Figure 2.6, with gray central area of side that is perpendicular to its plane. The corresponding moment is via I_z (L). The moment of the large triangle, through the side 2L is I_z (2L). These two parameters are related in two ways:

1. The required shape and surface mass density, the moment of inertia scales. Thus

$$I_z(2L) = 16I_z(L) \tag{2.2}$$

The large triangle can be described through rigid assembly of the small central triangle and the three adjacent ones. The parallel axis theorem yields:

$$I_z(2L) = (L) + 3[(L) + m(L)] \tag{2.3}$$

This formula involves the mass of the small triangle, the surface mass density, and L is the distance between the centers of mass of the side triangles and the axis.

Combining these two expressions, we obtained:

$$I_z = L43 - \sqrt{48} \tag{2.4}$$

2.2.6.2. The Y-axis

The axis contained in the plane of the triangle goes through the center of mass and a vertex. Utilizing the same strategy, the expression becomes:

$$I_y(2L) = 16(L)I_y \tag{2.5}$$
$$I_y(2L) = 2I_y(L)| + 2\left[I_y(L) = m(L)(L/2)^2\right]$$

On the equation’s right side, the first term corresponds to the central and top triangles (both their centers of mass are on y-axis) and the second one to the side triangles, as their centers are shifted.

$$I_y(L) = \frac{\mu L\sqrt[4]{3}}{96} I_2(L)/2 \tag{2.6}$$

In fact, the third-order symmetry is isotropic in the plane of the triangle in a two-dimensional space, which means that the inertia tensor has the same rate for any axis in this plane. The inertia tensor is:

$$\mathrm{I}= \begin{bmatrix} I_1(L) & 0 & 0 \\ 0 & I_1(L) & 0 \\ 0 & 0 & I_z(L) \end{bmatrix} \tag{2.7}$$

The isotropy of a tonsorial property for a framework in fact does not have full rotational symmetry [18].

2.2.7. Fin Stabilizers

For comparison to other stabilization systems in the application of big ships' motion control, there are some other systems, such as a fin stabilizer. At a downward angle, the fin is mounted beneath the waterline of a yacht that laterally appears. A hydraulic framework counteracts the roll, which may be caused by either waves or wind, and its fins are controlled by PC, which can change their angle [26].

Since the 1990s, stabilizer balances have been used in recreational yachts. Through innovative methods, fins have been efficient in countering movement powers. Similar to gyro stabilizers, there have been some huge headways in balance innovation, which have empowered them to become successful, unless a yacht is in a stationary position [28, 36]. Accessible blades crease up near the frame to diminish drag, but not at the case of "Zero Speed Stabilization". Furthermore, they even withdraw to diminish surface zone of the two planes bringing about less loss of speed that takes place because of balance drag. It may lose some speed because of drag by means of a customary stabilizer [25].

2.2.7.1. Fin Stabilizers' Advantages

1. Fin stabilizers highly decrease pitch and roll.
2. They can be placed in yachts from 50 feet to gage yachts (300ft+).
3. Its performance depends on the sort of fin stabilizer framework; however, it works while the ship is stationary or anchored.
4. In yachts, fin stabilizers take up a minimal amount of internal space[28].
5. To decrease drag to maintain a yacht's performance, the newer fin frameworks are optimized.
6. Typically, they cost less than gyros and require less maintenance[36].
7. Gyro does not need time to warm up, which can be turned on and off by a switch with a single flick.
8. When the integrity of the hull is compromised, the fins get hit with debris to break away.

2.2.7.2. Fin Stabilizer’s Disadvantages

1. The damage can be made to the exterior fin appendages that can lead to floating debris [36].
2. The yacht loses speed due to the increased drag from the fins underwater after adding stabilizer fins.
3. If the stabilizer fins are added later, extra reinforcement will be needed in the hull area surrounding the fin that results in extra costs, unless it is installed on a new yacht. In that case, a manufacturer reinforces the area where the fins are attached.

2.3. MARINE GYROSTABILIZER

In sea waves, the marine gyrostabilizer decreases the movement of a vessel. The device consists of a flywheel, which is mounted on a gimbal outline, permitting two of the three conceivable rotational degrees. Throughout the flywheel gimbaled inside the edge, the gimbal outline stays at that point unbendingly mounted to the structure of the vessel. The device is installed in the motor room of the vessel.

2.3.1. The Mechanism of Gyrostabilizers

The marine gyrostabilizers provide balancing mechanism according to operational standards. Generally, the captain, the team, and the shipyard work force monitor any new and energizing moves to carry out adjustment arrangements. In a gimbal outline, the gyro contains a mounted flywheel, which permits two of the three conceivable rotational degrees of flexibility. Throughout the flywheel gimbaled inside the frame, the gimbal outline stays at the point, which is unbendingly mounted to the body of the vessel.

2.3.2. The Torque of Gyro-Stabilizing

The gyro-settling torque is generated through three inter-twined parts. Every part is together through moment incidents, yet each one of them stays independent. Once the flywheel starts turning, the accompanying process prompts the advancement of a balancing out torque that restricts the rolling motion; otherwise, waves can lead to vessel rolling [28].

1. Rolling motion: It arises by spinning flywheel to form a precession motion [29].
2. Precession motion: It takes place by spinning flywheel to form stabilizing torque.

The gyro-dynamics physically cause these inter-twined actions, and if the flywheel spins in the opposite direction, the stabilizing torque will be identical, while the induced precession motion will be in the opposite direction. Figure 2.7 shows the gyro-stabilizing torque.

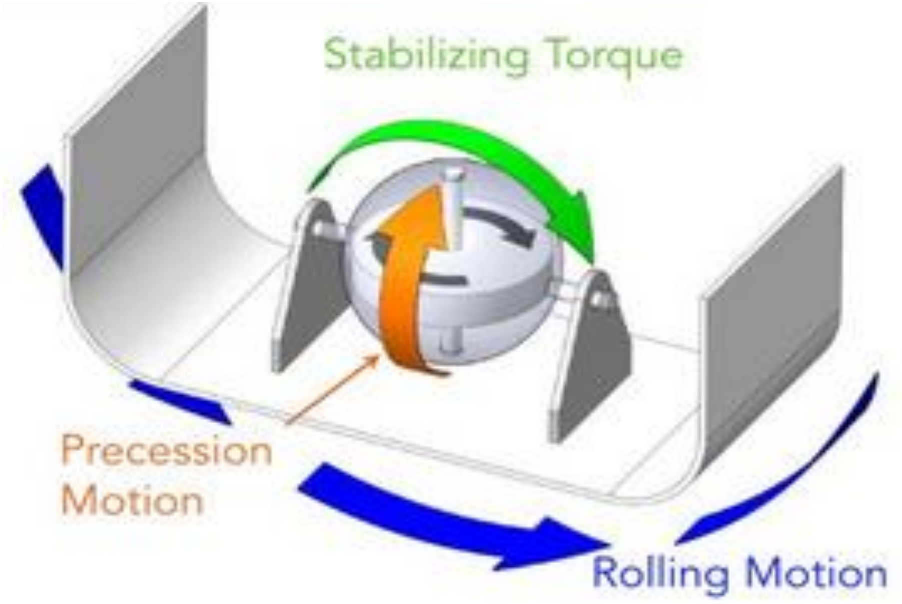
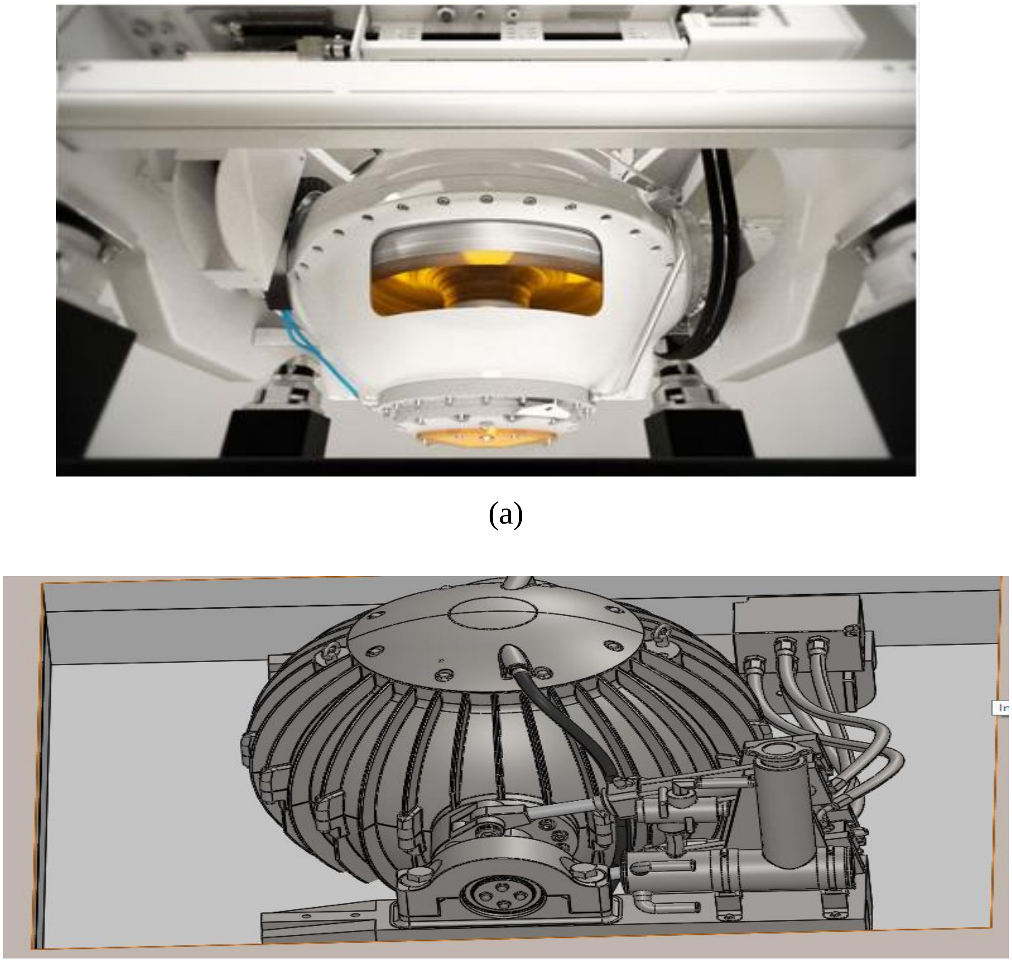


Figure 2.8. Gyro-Stabilizing Torque [24].

2.4. GYROS PROVIDE A HIGHER QUALITY OF COMFORT

A gyro's roll stabilizes out torque and stays shaped by means of the movement itself; so, there is no time deferral, or slack between the wave-incited movement, and the settling torque is delivered through a characteristic precession gyrostabilizer. Figure 2.8 shows the gyro's roll stabilizing torque. The outcome is an incredibly smooth utilization of the huge balancing out torques. Practically, the experience of turning the gyro on is a very basic level. There is essentially a quiet, unwinding reduction in motion. This must be experienced to comprehend. For a long time, the yachting group has trusted that the tradeoff for reduction in motion was disagreeable. This is the case when there is a quiet, unwinding diminishment in motion.



(a)

(b)

Figure 2.9. a), b) A gyro's roll stabilizing torque [15].

2.5. DIFFERENCES BETWEEN FINS AND GYROS

1. **Captains do not run zero speed fins when guests are swimming** near the yacht for safety reasons.

2. **Decreased Drag and higher hull efficiency** can be assured by choosing a gyro that has more than zero-speed blades that bring about higher speed, increased range, and fuel savings. The tradeoff is between the expansion in mass between a blade and a gyro.
3. **The expanded mass results in frame drag cost**, but when contrasted with the drag of wasteful zero-speed blades, a huge net reduction in drag is accomplished.
4. **No risk of grounding damage:** Balancing out blades may be harmed through different factors. This often brings about tedious and costly dry-docking.
5. **No equipment outside the engine room** is assured because the gyrostabilizer cannot be in the motor room, and besides, there is no necessity for specialized work force to operate or maintain blades.
6. **No dry-docking for maintenance ever:** Generally, dry-docking is a hectic period, which requires attention. A VEEM Gyro can be fully maintained (including major over-haul) within the vessel[18].
7. **Simple installation:** There is no need to run cables and piping through frame penetrations. When the gyro is a fully self-contained item, it saves a lot of time, effort, and capital that may be otherwise spent on coordinating frame penetrations, cable runs, and piping runs through the hull[37].
8. **Gyros alone cannot control,** so they are installed with transom flaps or interceptors. A gyrostabilizer cannot sustain a stabilizing torque for extended time. This means that steady-list angles due to wind heel or induced throughout turning maneuvers cannot be corrected by a gyro, which is acting alone.
9. **To optimize trim and speed** and to manage list angles, it is recommended that the gyro is installed through either transom flaps or interceptors. While doing so, a user gets comfort and low-drag benefits of the gyro, and besides, the user also gets steady state trim and list control. Both trim flaps and interceptors are extremely efficient at controlling the steady state trim and list. Both solutions also maintain clean hull lines, which are free of appendages and their costs[18].

2.6. GYROS MUST BE LOCATED ON THE VESSEL CENTERLINE

Because a gyrostabilizer produces pure torque, it can be theoretically located anywhere on the vessel. The stabilizing torque always opposes the rolling torque whether it is on or away from the vessel's centerline. To avoid high vertical accelerations that might shorten the life of the bearings, it is recommended that the units should located in the middle of ships[18]. When required, it is possible to relocate them up to 70% of LWL. As long as the vessel's overall mass distribution is maintained, there is absolutely no performance disadvantage to relocating the gyros away from the center-line[38].

The flexible rubber isolation mounts should transversely support to prevent the overload[39]. The convenience of electrical power supply and suitably strong supporting structure result in the gyro that is located within the engine room. This has the added benefit of enclosing the gyro within a noise-lagged space. The gyros remain located outside the engine room, but noise isolation considerations should be addressed.
Gyrostabilizers can be conveniently positioned away from the owner's spaces. This helps eliminating the annoying night-time noise and ensures that the service technicians do not need access to the owner's spaces. Figure 2.9 shows the gyrostabilizer placement and movement in Figure 2.10, and 2.11, which show the gyrostabilizer location and its physical movement.

2.6.1. The Gyro Can Be Located

1. Up to 70% LWL forward of the transom.
2. Off the centerline.
3. Up to 2m above the waterline.

A gyro can be located as shown in the figures below: -

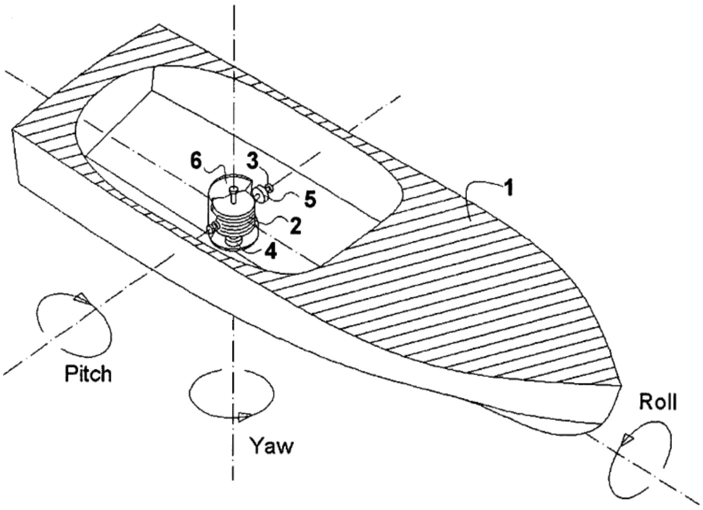


Figure 2.10. A gyrostabilizer location and movement [40].

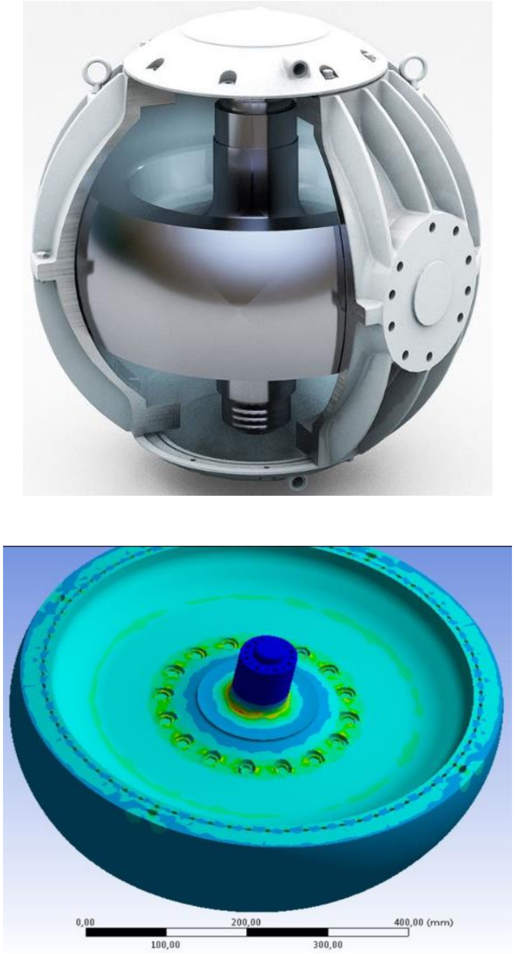


Figure 2.11. A gyrostabilizer location and movement [40].

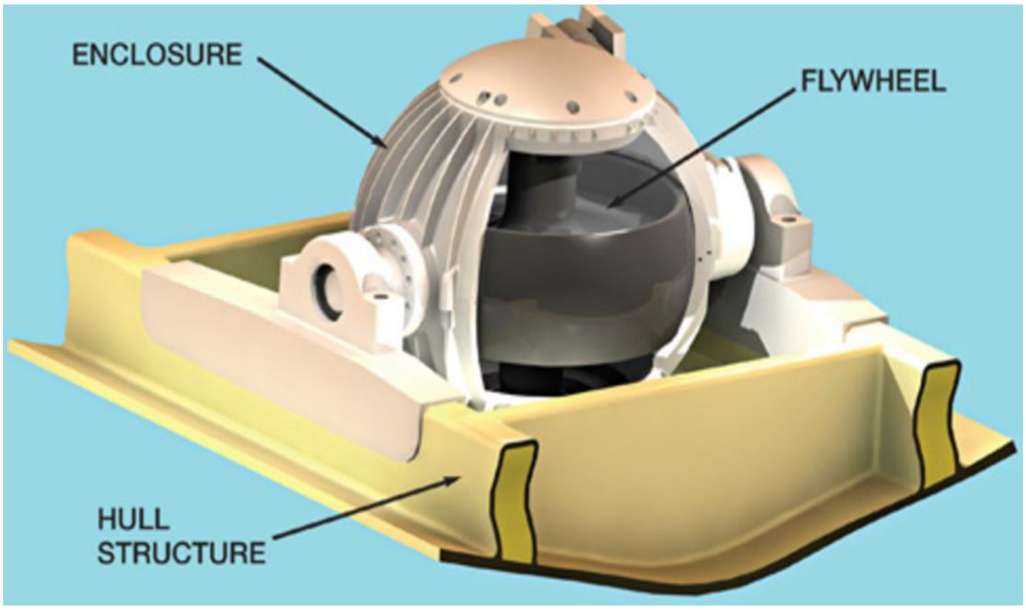


Figure 2. 12. A gyrostabilizer location and physical movement [40].

2.7. ADVANTAGES AND DISADVANTAGES OF GYRO STABILIZERS

2.7.1. Advantages

Gyros' area is much smaller for a stabilization device and they supply much greater stabilization per pound than the inert counterweight.

2.7.2. Disadvantages

The gyros are expensive, but not in camera terms. They can be rented if the mounts are already designed and built .Working with a rental company that develops some mounts is helpful in gyro installation. Gyros should be rented when they are needed. Kenyon rents gyro stabilizers. Also, a Barney should be added to them; it adds weight where needed. Bari foil or a wrap blanket of sand tubes help dealing with the sound issue[40]. A sound expert can be consulted to deal with the noise. Pan and tilt speeds are limited but the smooth moves are slower than this limit. They require another cable, battery and inverter[41]. Patterson (2009) has shown that a vessel hull stabilization framework utilizes hydrofoils, which are mounted on the vessel. The hydrofoils produce a counteracting force to the wave force that stabilizes the vessel. The hydrofoil is connected to the vessel in both passive and active modes. The hydrofoil consists of many configurations that include several attached struts and foils, which provide counteracting forces in response to wave actions [42].

Scientists reported that a fin stabilization framework minimizes roll about the longitudinal axis of the boat during sharp cornering at very high speeds[43]. In one form, equipment such as a machine gun is mounted to the bow of the boat and targets are adapted to be engaged in high-speed maneuvers when cornering and the deck of the boat is not excessively rolled whereby blocking visibility in a turn. Lang Lois, J. R. (2017) has shown that the problem of pitch stabilization of ships is considered for different vessels of varying sizes with application to both commercial and military craft[44].This approach considers fin location in the stern region, the effect of the propeller race, specific control framework and command rules, and special high-lift hydrofoils that are dependent on flow control. Outcomes of the program to date have been presented based on theoretical analysis and actual demonstration on a small vessel at the sea. The beneficial outcomes obtained on a 12.80 m (42 ft) cabin cruiser when it was equipped with controlled fins in at the marine tests in the Pacific Ocean, which support the basic concept of achieving useful pitch stabilization of ships in a seaway [45].

PART 3

OCEAN WAVES AND KINEMATICS OF YACHT MOTION

3.1. OCEAN WAVES AND WAVE SPECTRA

Generally, the ocean waves are random with respect to time and space. In the maritime literature, the mentioned terms irregularly summarize the features of wave spectra and ocean waves. In fact, the most appropriate approach to understanding the ocean waves is the stochastic description. Usually, in the experimental work, the ocean waves have been assumed as random, while there are certain variations, which are stochastic in nature. The mentioned variations are considerably slower as compared to the sea surface variations, so they are assumed as stationary. This point of view also suggests that the sea elevation ζ(x, y, t) has(x, y) position, which has a stationary stochastic process[46]. The underlying stochastic models are developed based on the following simplifying assumptions:

1. At the specific time period and location, the sea surface is homogeneous (Gaussian stochastic method with zero mean) in a stationary position.
2. The surface elevation of the sea waves can be expressed as $S_{\zeta\zeta}(\omega)$, which is a standard formula to assess the waves' Power Spectral Density (PSD), which is commonly referred to as wave spectrum, and besides, it can be used to explain the distributed energy of the sea waves on the surface.
3. Figure 3.1 illustrates the wave energy in a frequency-time plot, which is calculated by measuring pressure gauges offshore in Southern California with spectra of waves. The arrival of dispersed wave trains from distant storms has been shown by the ridges of high wave energy. It is inversely proportional, and the slope of the ridge shows the relationship with distance from the storm, where:

D is distance in degrees

Here, θ is the direction of arrival of waves.

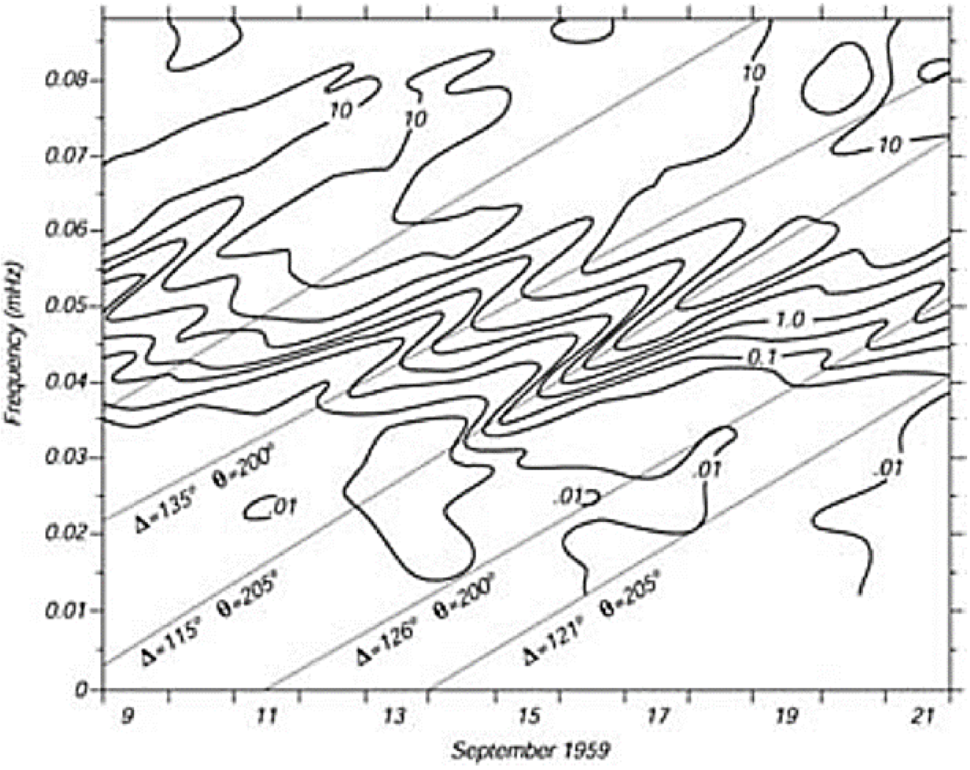


Figure 3.1. The wave energy on a frequency-time plot in Southern California [18, 47].

Statistically, a Gaussian assumption fully describes the expression “PSD Sζζ(ω)” as follows [18]:

$$E[\zeta] = 0 \tag{3.1}$$

$$E\zeta[\zeta(t)^2]=\int_0^\infty S\zeta\zeta(\omega)d\,\omega$$

From Gaussian, the state of the sea and its depth mainly affect the factors of sea and ocean waves. Generally, the surface elevation of the ocean is assessed through Gaussian irrespective of the state of the ocean in deep water. The spectrum of the wave slope is essential for some applications, which require a special derivative. The slope of the waves is calculated using the following formula:

$$(t, x) = \frac{d\xi\,(\mathrm{t}, x)}{dx} = -k\xi\ \cos(\omega t - kx - \varepsilon) \tag{3.2}$$

Where:

$\xi(x, y, z)$: The sea elevation at a position (x, y).

ε : The wave frequency

From this equation, the wave slope spectrum can be calculated using the following mathematical expression:

$$S'_{\xi\xi}(\omega) = \mathrm{k}^2\, S_{\xi\xi}(\omega) = \frac{\omega^4}{\mathrm{g}^2} S_{\xi\xi}(\omega) \tag{3.3}$$

Where:

Sζζ (ω) : the wave sea surface elevation

ε : The wave frequency

3.1.1. Statistics of Wave Period

The spectrum depends only on the frequency $S_{\xi\xi}(\omega)$ if we assumed that waves have a single-directional flow. The spectral moments or the statistical order moments "n" in $\xi(t)$ are given below [46]:

$$\mathrm{m}_{\xi}^{\mathrm{n}} = \int_0^{\infty} \omega^n S_{\xi\xi}(\omega) d\omega \tag{3.4}$$

Where:

m_{ξ}^{n}: The statistical moments of the spectrum

n: order

The definition of several statistical variables such as the wave period can be used for the moments of the spectrum, while the Gaussian method shows the relationships, which are given below:

1. The average wave period is defined by (1/average spectrum frequency) with the following equation:

$$T' or T_1 = 2\pi \frac{m_{\xi}^{0}}{m_{\xi}^{1}} \tag{3.5}$$

2. Zero-crossing wave period, which is defined by the following equation:

$$T_z = 2\pi \sqrt{\frac{m_{\xi}^{0}}{m_{\xi}^{2}}} \tag{3.6}$$

3. The average time period between crests (response maxima), which is defined by the following equation:

$$T_c = 2\pi \sqrt{\frac{m_{\xi}^{2}}{m_{\xi}^{4}}} \tag{3.7}$$

3.1.2. Statistics of Maxima

At zero level, the sea surface elevation of the Gaussian assumption means there is statistically symmetrical elevation. For wave record, maxima and minima are assumed as statistically symmetrical (at zero level). Usually, short-period oscillations are obvious from the wave records with maximum long-run oscillations in practice. There is expectation to have more than one maximum. As result, there will be positive minima as well. Figure 3.2 shows the Gaussian process and maxima. In stochastic function $\xi(t)$, maximum realization occurs if $\xi(t)$ is zero while minimum $\xi(t)$ is negative [46].

Figure 3. 2. Gaussian process and narrow-banded maxima [46].

Functions, such as $\xi(t)$, $\xi(t)$ and $\xi(t)$ give information about the distribution for obtaining maxima, in case the maxima appears as a realization of a random variable ξ. This spectral broadness controls the value of the probability density function (PDF) pξ(ξ).

Here:

$$e=\sqrt{1-\frac{T_c}{T_z}} \tag{3.8}$$

Exceeding the probability of amplitude $\xi_{1/n}$ is shown in the following equation:

$$p_r\left[\xi>\xi_{\frac{1}{n}}\right]=\frac{1}{n}=\int_{\xi_{\frac{1}{n}}}^{\infty}\frac{\xi}{m\xi_1^0}\exp\left(\frac{-\xi^2}{2m\xi_1^0}\right)d\xi \tag{3.9}$$

The average of observations (1/n-th) has been shown in Figure 3.3, which is defined through the following equation:

$$\xi'_{1/n} = n\int_{\xi_{\frac{1}{n}}}^{\infty} \frac{\xi^2}{m\xi_1^0}\exp\left(\frac{-\xi^2}{2m\xi_1^0}\right)d\xi \qquad (3.10)$$

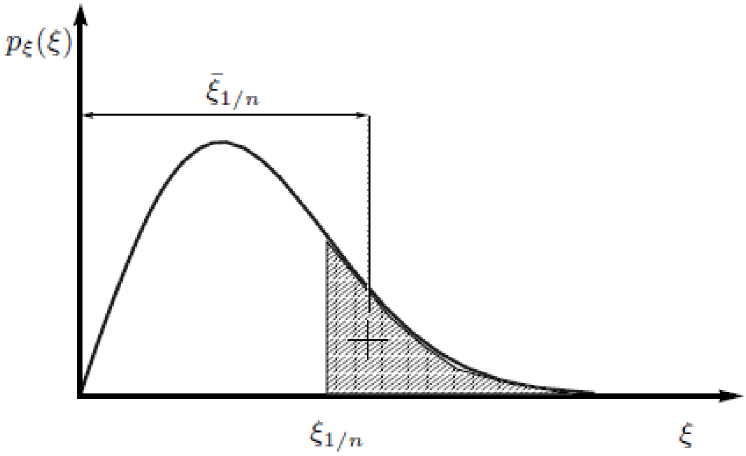


Figure 3.3. The 1/n-th highest observation definition [18].

Typically, 0.6 or less is the normal value for ocean waves or ship motion that is taken from records. In the most commonly used statistics, the statistics of maxima, which can be calculated in practice assuming ≈ 0; it results in 10% error while estimating $\bar{\xi}_{1/3}$ and $\bar{\xi}_{1/10}$. The following quantities are defined for evaluating the values pertaining to ship motion and waves with the assumption that it is a narrow-banded wave.

1. Average/mean value of wave amplitude can be defined by the following equation:
2. The significant wave amplitude can be expressed by the following equation:

$$\xi' = 1.5\sqrt{m_\xi^0}$$

$$\xi_{1/3} = 2\sqrt{m_\xi^0}$$

Where:

ξ' : Mean value of wave amplitude

$\xi_{1/3}$: Significant wave amplitude

The significant wave heights and their average show that 1/3rd of a wave can be defined by the following equation:

$$H_{1/3}(or Hs) = 4\sqrt{m_{\xi}^{0}}\sqrt{1-\frac{e^{2}}{1}} \tag{3.11}$$

Where:

Hs: Significant wave height

The significant wave height has been already mentioned. In addition, 0.6 is the spectral broadness for marine applications to justify the approximation (0.9055), which is the third factor in the previous equation. While applying it, the wave height defines the state of the ocean. Commonly, the sea state code describes the seaway, as Table 3.1 shows.

Table 3.1. The sea state definitions of World meteorological [18].

Code of sea state	H1/3 lower limit	H1/3 upper limit	Seaway description
0	0	0	Calm (glassy)
1	0	0.1	Calm (rippled)
2	0.1	0.5	Smooth (wavelets)
3	0.5	1.25	Slight
4	1.25	2.5	Moderate
5	2.5	4	Rough
6	4	6	Very rough
7	6	9	High
8	9	14	Very high
9	14	>14	Phenomenal

3.2. KINEMATICS OF YACHT MOTION

The dynamics indicate the branch, which explains different bodies' motion due to forces within the discipline of mechanics. It can be divided into the following two parts:

A. Kinematics

Kinematics study and characterization of motion for the geometrical aspects can be conducted without needing to evaluate forces and mass. It is based on transformations, variables, and reference frames.

B. Kinetics.

Kinetics characterizes those forces, which affect the motion.
The yacht motions' reference frames in seaway moves can be classified into six degrees of freedom(denoted as 6DOF). In general, three coordinates are used for defining translations while three coordinates for defining the orientation to describe the yacht motion. Two types of reference frames are used to describe the coordinates, which are:

1. Inertial frames
2. Body-fixed frames.

3.2.1. The n-Frame (North-east-down)

The n-frame (o_n, x_n, y_n, z_n) is constant to the Earth, the directions of these frames is as follows:

- The direction of x_n-positive axis is towards North
- The direction of z_n-positive axis is towards the Earth's center
- The direction of y_n-positive axis is towards the East

At an appropriate location and according to the yacht conditions, the origin is located on the water-free surface, which is considered as inertial. Such an assumption is reasonable considering the small magnitude of the velocity of marine vehicles. Figure 3.4 shows the yacht motion description with notation and sign conventions.

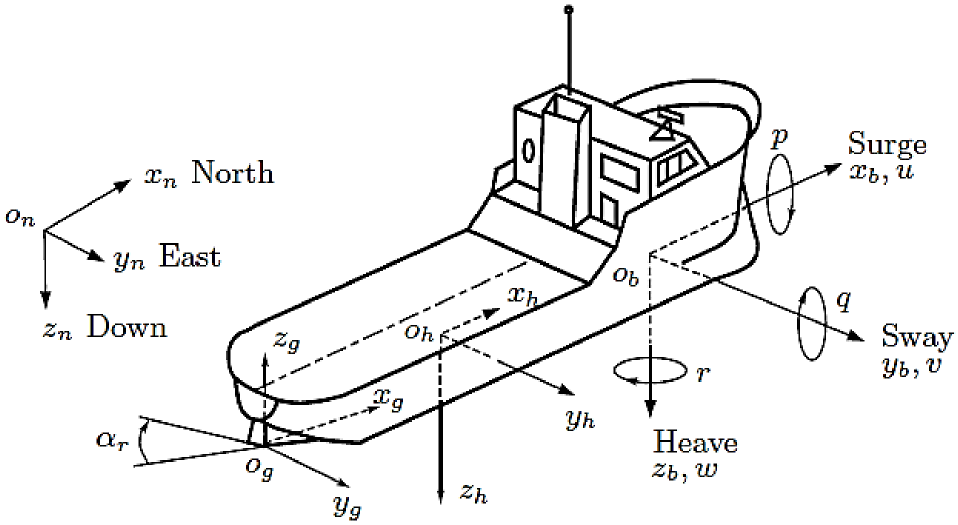


Figure 3.4. The yacht motion description with notation and sign conventions [18].

Figure 3.5 shows the yacht's reference frames and features. The geometric frame has origin og, the body-fixed has origin ob, and the hydrodynamic frame has origin oh where:

1. LCG: lateral center of gravity (distance)
2. CG: center of gravity
3. AP: aft perpendicular
4. Lpp: length between perpendiculars
5. VCG: vertical center of gravity (distance)
6. FP: front perpendicular
7. T: draught
8. BL: baseline.

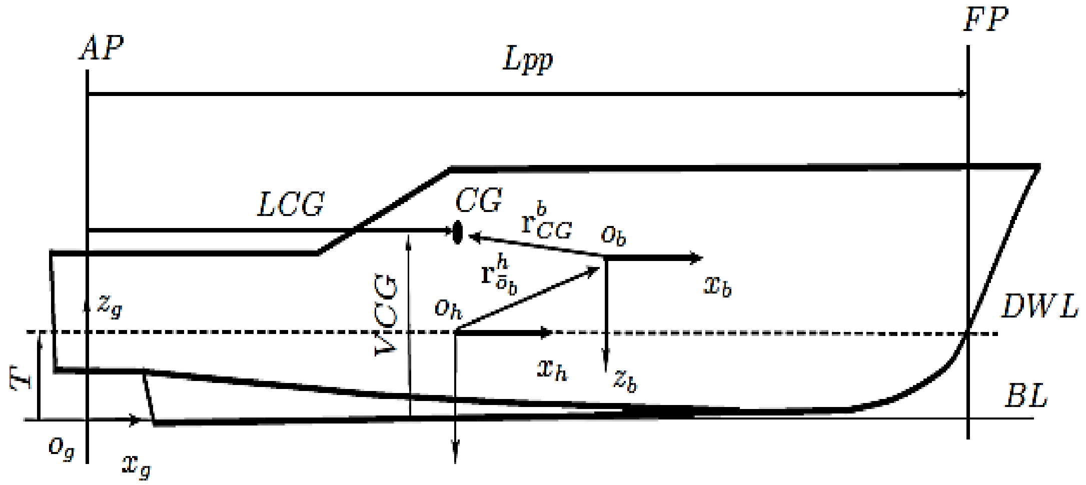


Figure 3. 5. The yacht's reference frames and main particulars [18].

3.2.2. Geometric Frame (g-frame; forward-starboard-up)

In this case, ag-frame (o_g, x_g, y_g, z_g) has been fixed with the hull; it has the following positive axis:

1. The axis y_g-positive points to the direction of the starboard
2. The axis x_g-positive points to the bow
3. The axis z_g-positive points in the upward direction.

Here, the location of origin is along the centerline of this frame at the aft perpendicular (AP) in addition to the baseline (BL) intersection, as shown in Figure 3.5.

3.2.3. Body-fixed Frame (b-frame; forward-starboard-down)

In this case, ab-frame (o_b, x_b, y_b, z_b) has been joined with the hull, while the directions are as follows:

1. The axis x_b-positive points in the direction of the bow
2. The axis z_b-positive points downwards
3. The axis y_b-positive points in the direction of the starboard

For coinciding with principal axes of inertia, this frame's axes have been selected for marine vehicles, while it also determines the frame origin ob.

3.2.4. Hydrodynamic Frame (h-frame; forward-starboard-down)

When yacht follows its path, the h-frame (oh, xh, yh, zh) isn't joined with the hull that continues its motion, while the positive axis points towards to following:

1. The axis xh-positive points in the forward direction in alignment with the yaw angle: $\psi 1$.
2. The axis zh-positive points downwards
3. The axis yh-positive points in the direction of the starboard

The origin oh is determined with the help of time-average position of the center of gravity.

3.3. VECTOR NOTATION

In vector notation, establishing a mathematical notation is essential because of the use of several reference frames. The mathematical notation allows the operator to identify acceleration, position and velocity on the yacht's different points of interest in the different frames. In addition, x is the generic point of interest on a yacht[46]:

1. The position of x can be denoted by r_x^f for frame f:

$$r_x^f = x_x^f \, f_x + y_x^f f_y + z_x^f \, f_z$$

$$r_x^f = \begin{bmatrix} x_x^f \\ y_x^f \\ z_x^f \end{bmatrix}$$

$$r_x^f = \begin{bmatrix} x_x^f & y_x^f & z_x^f \end{bmatrix} \qquad (3.12)$$

Where:

1. r_x^f - represents the position of x for frame f.
2. The velocity of x can be denoted by V_x^f with respect to a frame f.
3. The acceleration of x can be denoted by $\ddot{\mathrm{v}}_x^f$ with respect to a frame f.
4. The b-frame orientation and the Euler angles assume the a-frame.
5. Frame b's relative angular velocity can be denoted by ω_{ab}^c for frame a that is decomposed into frame c.

The following is the vectors equation of the cross product:

$$axb = s(a)b$$

Where the skew-symmetric **S** matrix will be defined as follows:

$$s(\lambda) = -s^T(\lambda) = \begin{bmatrix} 0 & -\lambda_2 & \lambda_2 \\ \lambda_3 & 0 & -\lambda_1 \\ -\lambda_2 & \lambda_1 & 0 \end{bmatrix} \qquad (3.13)$$

$$\lambda = \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \end{bmatrix} \qquad (3.14)$$

3.4. COORDINATES OF YACHT MOTION

The coordinates that describe the yacht's motion can be classified as follows:

3.4.1. Sea Keeping and Maneuvering

Surface yacht operations are performed in different environmental conditions, where in each case; there are different hydrodynamic factors and assumptions. Traditionally, the study of dynamic vessels and yachts are separated into two main areas based on the results of all those, which are mentioned before:

3.4.1.1. Seakeeping

While the yacht keeps its speed and course constant, the seakeeping is linked to wave excitation.

3.4.1.2. Maneuvering

In calm water or when there is no wave excitation, maneuvering deals with the yacht motion. The maneuvering occurs with respect to the course changes and stopping, and the motion takes place with the help of propulsion units, control surfaces, and control devices. Nowadays, after the progress in the field of maneuvering and seakeeping, the motion of the yacht is described through coordinates and reference frames based on certain assumptions, which are made during maneuvering and seakeeping. In fact, these two areas of yacht motion study are popular, and their models accurately describe the characteristics of motion.

3.4.2. Reference Frames and Maneuvering Coordinates

The b-frame (**op)** coordinates are relative to the n-frame, as shown below, as they define the yacht's north-east-down position.

$$r_{op}^{n} = \begin{bmatrix} n \\ e \\ d \end{bmatrix} \tag{3.15}$$

Due to the position of the b- and n-frames, the yacht behavior can be identified throughout three consecutive rotations after taking into account both the mentioned frames. These rotations have been shown (3.14):

1. The **z_n** axis rotation where yaw **ψ** is the rotation angle

2. The $\mathbf{y_n}$ axis rotation where pitch $\boldsymbol{\theta}$ is the rotation angle
3. The $\mathbf{x_n}$ rotation axis where roll $\boldsymbol{\varphi}$ is the rotation angle

Euler angles are the name/type of the rotation angles when the rotations are accomplished in a specific order. We defined the Euler's angle vector as follows:

$$(-)_{nb} = \begin{bmatrix} \phi \\ \theta \\ \Psi \end{bmatrix} \tag{3.16}$$

Reference frames have defined components, which are shown in Table 3.2 and the yacht motion.

Table 3.2. Reference frames and adopted nomenclature [46].

Components	Name	Definitions frame
n	North position	n- frame
e	East position	n- frame
d	Down position	n- frame
φ	Roll angle	Euler angle
θ	Pitch angle	Euler angle
ψ	Heading or yaw angle	Euler angle
u	Surge velocity	b-frame
v	Sway velocity	b-frame
w	Heave velocity	b-frame
p	Roll rate	b-frame
q	Pitch rate	b-frame
r	Yaw rate	b-frame

3.4.3. Reference Frames and Seakeeping Coordinates

When a study of yacht motion is performed in seakeeping, the yacht is assumed to be moving at a steady and constant average speed. It shows that the yacht has acquired equilibrium during motion, while in the wave-induced first order motion; the wave action oscillates the yacht. The seakeeping theory of yacht motion is based on this fundamental assumption. The h-frame is utilized to describe the motion of the yacht keeping in view the seakeeping theory. In addition, assuming that maneuvering is significantly slower as compared to the wave-induced motion, a yacht should be allowed to maneuver. Thus, the h-frame is utilized to describe the motion. Figure 3.6 shows the horizontal plane angles. The seakeeping coordinates and the generalized perturbation coordinates are defined in the h-frame, as shown in the figure below.

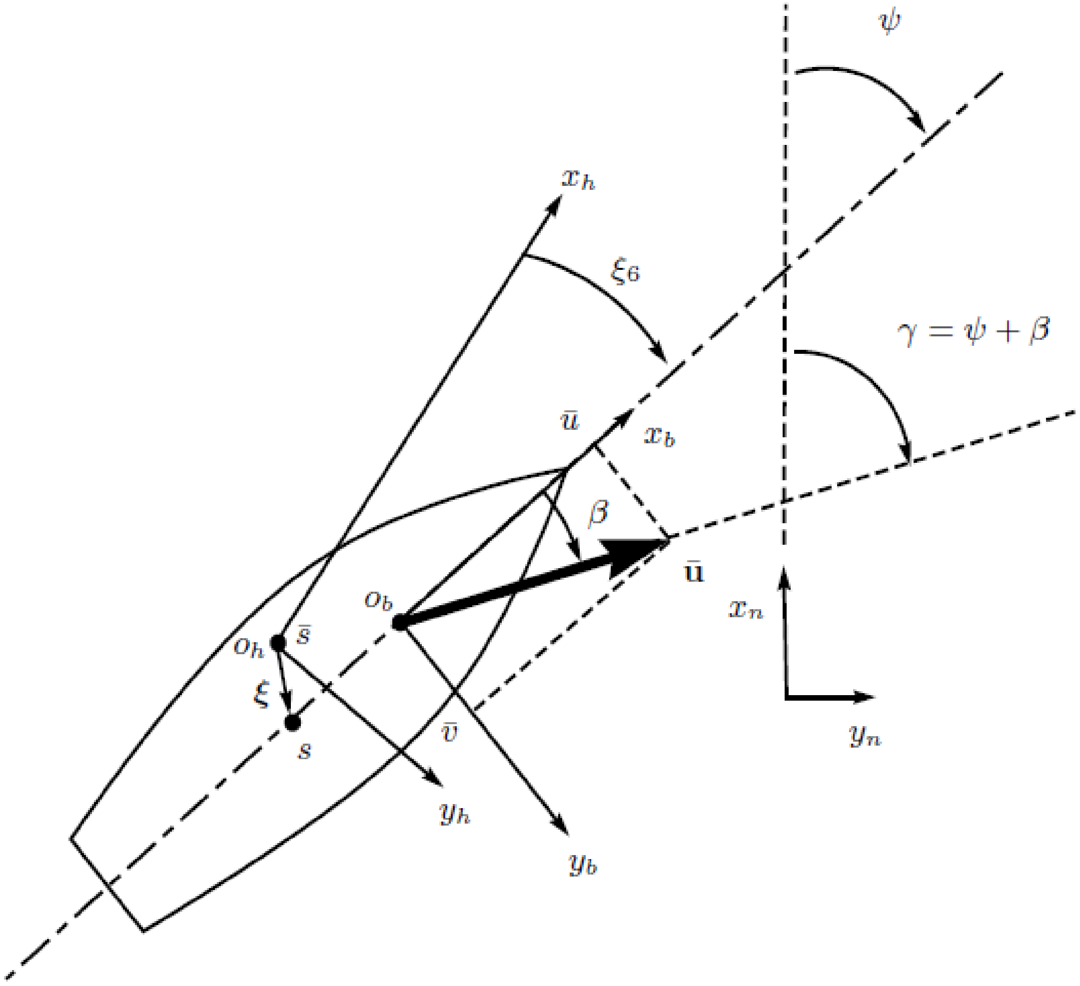


Figure 3.6. The horizontal plane angles [46].

$$\zeta = [\zeta_1, \zeta_2, \zeta_3, \zeta_4, \zeta_5, \zeta_6]^T \tag{3.17}$$

The linear coordinates describe the yacht position, as shown in Figure 3.6, which are as follows:

1. ξ_2 sway displacement,
2. ξ_1 surge displacement,
3. ξ_3 heave displacement,

The Euler angles are used to consider the h-frame orientation keeping in view the b-frame orientation, which are the angular coordinate's ξ_4, ξ_5, ξ_6:

$$(-)_{hb} = \begin{bmatrix} \xi_4 \\ \xi_5 \\ \xi_6 \end{bmatrix} = \begin{bmatrix} \phi \\ \theta \\ \Psi - \Psi' \end{bmatrix} \tag{3.18}$$

These angles are:

1. ξ_6 yaw perturbation angle.
2. ξ_4 roll perturbation angle,
3. ξ_5 pitch perturbation angle,

3.4.4. Z-Axis Angles

In case of b-frame, the velocity vector of the yacht is defined as follows:

$$\bar{u} = \left[\bar{u}, \quad \bar{v}, \quad \bar{w}\right]^T \tag{3.19}$$

Where:

$$\begin{aligned} \mathrm{u} &= \bar{\mathrm{u}} + \delta\mathrm{u} \\ \mathrm{v} &= \bar{\mathrm{v}} + \delta\mathrm{v} \\ \mathrm{w} &= \bar{\mathrm{w}} + \delta\mathrm{w} \end{aligned} \tag{3.20}$$

In addition, the $\overline{\mathrm{w}}$ =0for on-the-surface vessels. The approximate sway and surge velocities $\overline{\mathrm{v}}$ and $\overline{\mathrm{u}}$ remain the same for b and h-frames while slow maneuvering. We denoted the surge velocity as:

$$\mathrm{u} = \overline{\mathrm{u}}^{\mathrm{h}} \approx \overline{\mathrm{u}} \tag{3.21}$$

Commonly, this type of notation applies in hydrodynamics and seakeeping.

3.5. THEORIES OF ANGULAR MOMENTUM OF A RIGID BODY

3.5.1. The Angular Momentum with Respect to a Fixed Point

Figure 3.7 shows the angular momentum of the particle *i* about point O:

$$\mathrm{dL}_{\mathrm{i/O}}=\mathrm{r}_{\mathrm{i}}\times\mathrm{v}_{\mathrm{i}}\mathrm{dm}_{\mathrm{i}} \tag{3.22}$$

After adding up, we get:

$$\mathbf{L}_O = \sum_i (\mathbf{r}_i \times \mathbf{v}_i dm_i) \tag{3.23}$$

To find out the point I (3.23):

$$\begin{aligned} \mathbf{v}_i &= \mathbf{v}_G + \mathbf{w} \times \mathbf{r}_{i/G} \\ \mathbf{r}_i &= \mathbf{r}_G + \mathbf{r}_{i/G} \end{aligned} \tag{3.24}$$

Where:

$\mathbf{r}_{\mathrm{i}}$ is the position vector of particle “” with respect to fixed origin O
$\mathbf{r}_G$ is the position vector of the mass centre *G*
$\mathbf{r}_{\mathrm{i/G}}$ is a relative position vector of the particle I with respect to G
$\mathbf{v}_i$ is the velocity

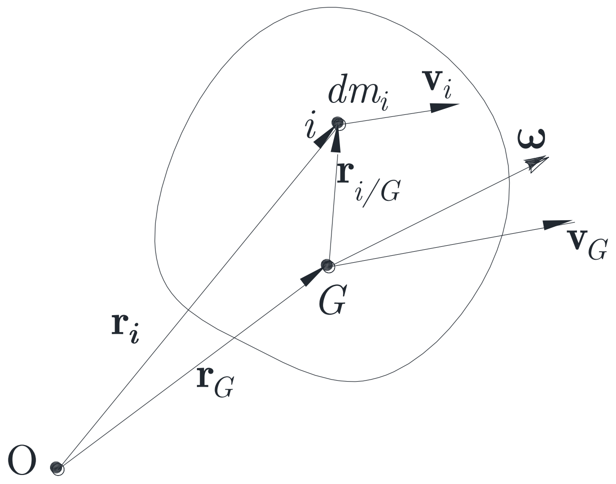


Figure 3.7. Angular momentum of the body with respect to the fixed-point O.

In this situation, it can be:

$$\mathbf{L}_O = \sum_i (\mathbf{r}_G + \mathbf{r}_{i/G}) \times (\mathbf{v}_G + \mathbf{w} \times \mathbf{r}_{i/G}) dm_i \tag{3.25}$$

When we expand the above equation, the following expression is obtained:

$$\begin{gathered} \mathrm{L_O} = \sum_{\mathrm{i}} (\mathrm{r_G} + \mathrm{r_{i/G}}) \times (\mathrm{v_G} + \mathrm{w} \times \mathrm{r_{i/G}}) \mathrm{dm_i} \\ \mathrm{L_O} = \sum_{\mathrm{i}} (\mathrm{r_G} \times \mathrm{v_G} \mathrm{dm_i} + \sum_{\mathrm{i}} (\mathrm{r_G} \times (\mathrm{w} \times \mathrm{r_{i/G}}) \mathrm{dm_i} \\ + \sum_{\mathrm{i}} \mathrm{r_{i/G}} \times \mathrm{v_G} \mathrm{dm_i} + \sum_{\mathrm{i}} \mathrm{r_{i/G}} \times (\mathrm{w} \times \mathrm{r_{i/G}}) \mathrm{dm_i} \\ \sum_{\mathrm{i}} (\mathrm{r_G} \times (\mathrm{w} \times \mathrm{r_{i/G}}) \mathrm{dm_i} = 0 : \sum_{\mathrm{i}} \mathrm{r_{i/G}} \times \mathrm{v_G} \mathrm{dm_i} = 0 : \end{gathered} \tag{3.26}$$

For mass centre: $\sum \mathbf{r}_{i/G} dm_i = 0$,

Here, $\mathbf{r}_G$ and $\mathbf{v}_G$ are common for all the particles.

$$\sum_i \mathbf{r}_G \times \mathbf{v}_G dm_i = \mathbf{r}_G \times \mathbf{v}_G \sum dm_i = \mathbf{r}_G \times \mathbf{v}_G m = \mathbf{r}_G \times \mathbf{P} \tag{3.27}$$

Where

P: Linear momentum

Figure 3.8 shows the rigid body rotation about a fixed point while in general, it will be as follows:

$$\mathbf{L}_O = \mathbf{r}_G \times \mathbf{P} + \sum_i \mathbf{r}_{i/G} \times (\mathbf{w} \times \mathbf{r}_{i/G}) dm_i \tag{3.28}$$

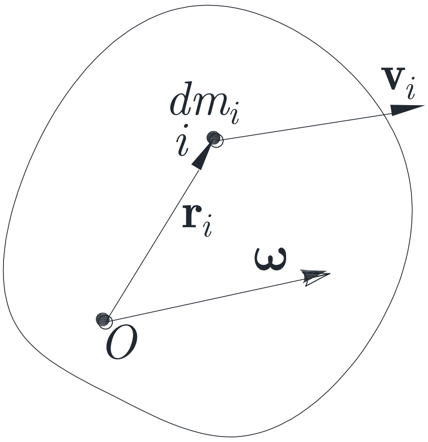


Figure 3.8. Rigid body rotation about a fixed point.

The angular momentum for a rigid body during rotation about a fixed point, where the centre and the mass can be expressed through the following equation (3.29):

$$\mathbf{L}_O = \sum_i \mathbf{r}_i \times (\mathbf{w} \times \mathbf{r}_i) dm_i \tag{3.29}$$

2.5.2. Motion of Rigid Body in Space

2.5.2.1 Theory of Space Motion

If the particles are infinitesimal, the number will be large. Figure 3.9 shows the rigid body rotation through a fixed point, while the right-handed coordinates with unit vectors are expressed as follows:

$$
\begin{aligned}
&\mathbf{L}_O = \sum_i \mathbf{r}_i \times (\mathbf{w} \times \mathbf{r}_i) dm_i = \iiint \mathbf{r} \times (\mathbf{w} \times \mathbf{r}) dm_i, \\
&\mathbf{r} = x\mathbf{i} + y\mathbf{j} + z\mathbf{k}, \\
&\mathbf{w} = \omega_x \mathbf{i} + \omega_y \mathbf{j} + \omega_z \mathbf{k}.
\end{aligned}
\tag{3.29}
$$

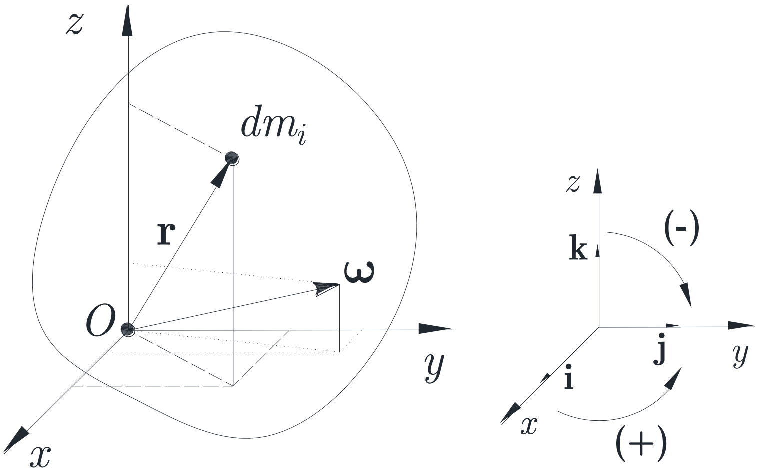


Figure 3. 9. Rigid body rotation about a fixed point and right-handed coordinates with the unit vectors.

Where,

$$
\begin{aligned}
&(\mathbf{w} \times \mathbf{r}) = (\omega_x \mathbf{i} + \omega_y \mathbf{j} + \omega_z \mathbf{k}) \times (x\mathbf{i} + y\mathbf{j} + z\mathbf{k}) \\
&\text{hint: } \mathbf{i} \times \mathbf{i} = \mathbf{j} \times \mathbf{j} = \mathbf{k} \times \mathbf{k} = \mathbf{0} \\
&= \mathbf{k}(\omega_x y) - (\omega_x z)\mathbf{j} - (\omega_y x)\mathbf{k} + (\omega_y z)\mathbf{i} + (\omega_z x)\mathbf{j} - (\omega_z y)\mathbf{i} \\
&= (\omega_y z - \omega_z y)\mathbf{i} + (\omega_z x - \omega_x z)\mathbf{j} + (\omega_x y - \omega_y x)\mathbf{k} \\
&\mathbf{r} \times (\mathbf{w} \times \mathbf{r}) = (x\mathbf{i} + y\mathbf{j} + z\mathbf{k}) \times (\omega_y z - \omega_z y)\mathbf{i} + (\omega_z x - \omega_x z)\mathbf{j} + (\omega_x y - \omega_y x)\mathbf{k} \\
&= 0 + (\omega_z x^2 - \omega_x xz)\mathbf{k} - (\omega_x xy - \omega_y x^2) - (\omega_y yz - \omega_z y^2)\mathbf{k} + 0 + (\omega_x y^2 - \omega_y yx)\mathbf{i} \\
&(\omega_y z^2 - \omega_z zy)\mathbf{j} - (\omega_z zx - \omega_x z^2)\mathbf{i} \\
&= (\omega_x y^2 - \omega_y yx - \omega_z zx + \omega_x z^2)\mathbf{i} + \\
&(\omega_y z^2 - \omega_z zy - \omega_x xy + \omega_y x^2)\mathbf{j} + \\
&(\omega_z x^2 - \omega_x xz - \omega_y yz + \omega_z y^2)\mathbf{k} \\
&= (\omega_x (y^2 + z^2) - \omega_y yx - \omega_z zx)\mathbf{i} + \\
&(\omega_y (z^2 + x^2) - \omega_z zy - \omega_x xy)\mathbf{j} + \\
&(\omega_z (x^2 + y^2) - \omega_x xz - \omega_y yz)\mathbf{k}
\end{aligned}
\tag{3.30}
$$

$$
\begin{aligned}
&\mathbf{L}_O = \iiint \mathbf{r} \times (\mathbf{w} \times \mathbf{r}) dm \\
&= \left[\iiint \omega_x (y^2 + z^2) dm - \iiint \omega_y xy dm - \iiint \omega_z xz dm \right] \mathbf{i} + \\
&\left[-\iiint \omega_x xy dm + \iiint \omega_y (z^2 + x^2) dm - \iiint \omega_z yz dm \right] \mathbf{j} + \\
&\left[-\iiint \omega_x xz dm - \iiint \omega_y yz dm + \iiint \omega_z (x^2 + y^2) dm \right] \mathbf{k} \\
&\quad I_{xx}\omega_x - I_{xy}\omega_y - I_{xz}\omega_z \ \mathbf{i} + (-I_{yx}\omega_x + I_{yy}\omega_y - I_{yz}\omega_z)\mathbf{j} + (-I_{zx}\omega_x - I_{zy}\omega_y + I_{zz}\omega_z)\mathbf{k}
\end{aligned}
\tag{3.31}
$$

In such a case, using matrix notation with directional components, and the equation given above, can be simplified as follows:

$$
\begin{aligned}
\mathbf{L}_{Ox} &= I_{xx}\omega_x - I_{xy}\omega_y - I_{xz}\omega_z \\
\mathbf{L}_{Oy} &= -I_{yx}\omega_x + I_{yy}\omega_y - I_{yz}\omega_z \\
\mathbf{L}_{Oz} &= -I_{zx}\omega_x - I_{zy}\omega_y + I_{zz}\omega_z \\
\mathbf{L}_O &= \begin{bmatrix} I_{xx} & -I_{xy} & -I_{xz} \\ -I_{yx} & I_{yy} & -I_{yz} \\ -I_{zx} & -I_{zy} & I_{zz} \end{bmatrix} \begin{Bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{Bmatrix}
\end{aligned}
\tag{3.32}
$$

Where:

1. L_{Ox}, L_{Oy} and L_{Oz} are the x, y, and z components, respectively,
2. x, y and z axis are the components of angular momentum in a fixed coordinates system.
3. I_{xx} with respect to x axis is the mass moment of the body inertia.
4. I_{xy} with respect to xy plane is the mass moment of inertia.

Like the case of x axis, the other inertia components have been named. Components of angular velocity vector **ω** are ω_x, ω_y and ω_z. Utilizing the privies equations, the angular momentum of a rigid body within a fixed point can be explained as follows:

$$
\mathbf{L}_O = \left[I_O \right] \mathbf{w} \tag{3.33}
$$

$$
\mathbf{L} = \left[I \right] \mathbf{w} \tag{3.34}
$$

The inertia tensor or inertia matrix is shown as I_o. A tensor is higher than a vector, but it is not a scalar or a vector quantity.

2.5.3. Principle Axis

When the principle axis coincides with a symmetric plane, it is not necessary for the point of passage to be the centre of the mass, and the principle axis is perpendicular to a symmetrical plane. If it passes through the centre of the mass, it is called central principle axis. The plane components of inertia terms will be zero for a principle axis. In this case, it can be explained as follows:

$$\begin{aligned}\mathbf{L}_x &= I_{xx}\omega_x\\ \mathbf{L}_y &= I_{yy}\omega_y\\ \mathbf{L}_z &= I_{zz}\omega_z\end{aligned}$$

$$\mathbf{L}=\begin{Bmatrix}\mathbf{L}_x\\ \mathbf{L}_y\\ \mathbf{L}_z\end{Bmatrix}=\begin{bmatrix}I_{xx} & 0 & 0\\ 0 & I_{yy} & 0\\ 0 & 0 & I_{zz}\end{bmatrix}\begin{Bmatrix}\omega_x\\ \omega_y\\ \omega_z\end{Bmatrix} \tag{3.35}$$

The angular velocity vector cannot coincide with angular momentum vector, as shown in Figure 3.10, unless $I_{xx}=I_{yy}=I_{zz}$.

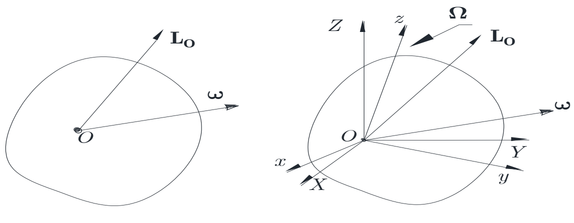


Figure 3.10. Angular velocity and angular momentum.

Figure 3.11 explains the case of body symmetry, where the axis of symmetry will be a principal axis. Unless the symmetry condition is satisfied, the principal axis cannot be identified through direct observation.

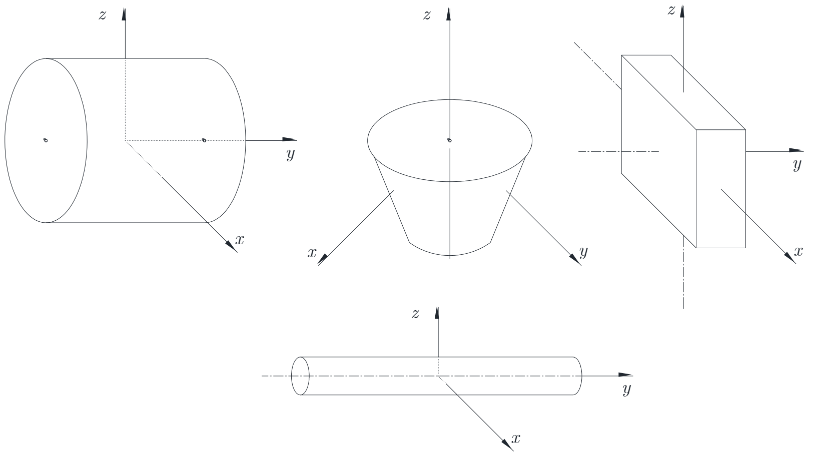


Figure 3.11. Examples of principal axis with some engineering cases.

3.5.4. Theory of Externally Applied Torques

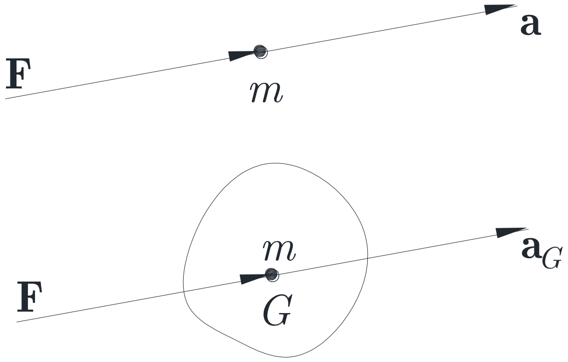


Figure 3.12. Particle and rigid body translational motion.

For any a particle or body, the translational motion acceleration is proportional to the applied force, and in the same direction; while its amplitude is *F/m*. The mass is a constant in this relation described as **F**=m**a**, when the force is applied at a fixed time. In fact, the below equation explains this case that is known as the Second Law of Motion for a constant mass.

$$\mathbf{F} = \frac{\mathrm{d}\mathbf{P}}{\mathrm{d}t} = \frac{\mathrm{d}}{\mathrm{d}t}(\mathbf{v}m) = m\frac{\mathrm{d}}{\mathrm{d}t}(\mathbf{v}) = m\mathbf{a} \tag{3.36}$$

In rotational motion, angular acceleration of the body for amplitude is *T/I*, where:

1. *T* is the applied torque.
2. *I* is the mass moment of inertia of the body with respect to rotation axis.

Equation 3.30 shows the applied Torque ***T*** that also represents time change of angular momentum of a rigid body.

$$\mathbf{T} = \frac{\mathrm{d}\mathbf{L}}{\mathrm{d}t} \tag{3.37}$$

The parameters of angular velocity and momentum can be determined in practical applications for a rigid body, if the applied torque T, and the inertial properties and rotation axis are known. The controlling angular momentum of rigid bodies is another way that produces external torque. Additional bearing force is produced by changing the direction of the angular momentum vector in the engines of airplanes in any rotation motion of aircraft in air, which are another design consideration of application of angular momentum. As an example, the amplitude of the angular momentum is constant, if the rotor of an engine of an airplane rotates at a constant angular velocity, for the rotor, it is expressed as:

$$I_{xx} = I_{yy} = I_{zz} \tag{3.38}$$

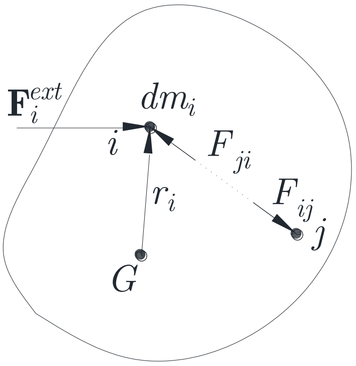


Figure 3.13. External force and moment.

In addition, on i, the total force is as following:

$$\mathbf{F}_i^{ext} + \sum_{i=1, i\neq j}^{n} \mathbf{F}_{ij} = \ddot{\mathbf{r}}_i dm_i \tag{3.39}$$

While, with respect to point G, the moment of these forces are:

$$\begin{aligned}
\mathbf{T}_G &= \sum_i^n \ddot{\mathbf{r}}_i \times (\mathbf{F}_i^{ext} + \sum_{i=1, i\neq j}^{n} \mathbf{F}_{ij}) \\
&= \sum_i^n \ddot{\mathbf{r}}_i \times \mathbf{F}_i^{ext} + \sum_i^n \sum_{i=1, i\neq j}^{n} \ddot{\mathbf{r}}_i \times \mathbf{F}_{ij} : \sum_i^n \sum_{i=1, i\neq j}^{n} \ddot{\mathbf{r}}_i \times \mathbf{F}_{ij} = 0 :
\end{aligned}$$

$$\mathbf{T}_G = \sum_i^n \mathbf{r}_i \times \ddot{\mathbf{r}}_i dm_i$$

$$\mathbf{T}_G = \dot{\mathbf{L}}_G$$

$$\mathbf{L}_G = \sum_i^n \mathbf{r}_i \times \dot{\mathbf{r}}_i dm_i \Rightarrow \dot{\mathbf{L}}_G = \sum_i^n \dot{\mathbf{r}}_i \times \dot{\mathbf{r}}_i dm_i + \sum_i^n \mathbf{r}_i \times \ddot{\mathbf{r}}_i dm_i : \sum_i^n \dot{\mathbf{r}}_i \times \dot{\mathbf{r}}_i dm_i = 0$$

$$\dot{\mathbf{L}}_G = \sum_i^n \mathbf{r}_i \times \ddot{\mathbf{r}}_i dm_i$$

$$\mathbf{L} = \begin{Bmatrix} \mathbf{L}_x \\ \mathbf{L}_y \\ \mathbf{L}_z \end{Bmatrix} \mathit{and}\ \mathbf{L}_x = I_{xx} w_x ; \mathbf{L}_x = I_{yy} w_y ; \mathbf{L}_z = I_{zz} w_z ; \text{principal axis (xyz)}$$

$$\begin{aligned}
&\mathbf{L} = I_{xx} w_x \mathbf{i} + I_{yy} w_y \mathbf{j} + I_{zz} w_z \mathbf{k}; \quad \mathbf{w} = w_x \mathbf{i} + w_y \mathbf{j} + w_z \mathbf{k}; \\
&\dot{\mathbf{L}} = \left.\frac{\mathrm{d}\mathbf{L}}{\mathrm{dt}}\right|_{XYZ} = \left.\frac{\mathrm{d}\mathbf{L}}{\mathrm{dt}}\right|_{xyz} + \mathbf{w} \times \mathbf{L}; \\
&= \mathbf{i} \left.\frac{\mathrm{d}\mathbf{L}_x}{\mathrm{dt}}\right|_{xyz} + \mathbf{j} \left.\frac{\mathrm{d}\mathbf{L}_y}{\mathrm{dt}}\right|_{xyz} + \mathbf{k} \left.\frac{\mathrm{d}\mathbf{L}_z}{\mathrm{dt}}\right|_{xyz} + \mathbf{w} \times \mathbf{L}; \\
&= I_{xx} \dot{w}_x \mathbf{i} + I_{yy} \dot{w}_y \mathbf{j} + I_{zz} \dot{w}_z \mathbf{k} + (w_x \mathbf{i} + w_y \mathbf{j} + w_z \mathbf{k}) \times (I_{xx} w_x \mathbf{i} + I_{yy} w_y \mathbf{j} + I_{zz} w_z \mathbf{k})
\end{aligned}$$

$$\begin{aligned}
&\dot{\mathrm{L}} = \mathrm{I}_{\mathrm{xx}} \dot{\mathrm{w}}_{\mathrm{x}} \mathrm{i} + \mathrm{I}_{\mathrm{yy}} \dot{\mathrm{w}}_{\mathrm{y}} \mathrm{j} + \mathrm{I}_{\mathrm{zz}} \dot{\mathrm{w}}_{\mathrm{z}} \mathrm{k} + (\mathrm{w}_{\mathrm{x}} \mathrm{i} + \mathrm{w}_{\mathrm{y}} \mathrm{j} + \mathrm{w}_{\mathrm{z}} \mathrm{k}) \times (\mathrm{I}_{\mathrm{xx}} \mathrm{w}_{\mathrm{x}} \mathrm{i} + \mathrm{I}_{\mathrm{yy}} \mathrm{w}_{\mathrm{y}} \mathrm{j} + \mathrm{I}_{\mathrm{zz}} \mathrm{w}_{\mathrm{z}} \mathrm{k}); \\
&= \mathrm{I}_{\mathrm{xx}} \dot{\mathrm{w}}_{\mathrm{x}} \mathrm{i} + \mathrm{I}_{\mathrm{yy}} \dot{\mathrm{w}}_{\mathrm{y}} \mathrm{j} + \mathrm{I}_{\mathrm{zz}} \dot{\mathrm{w}}_{\mathrm{z}} \mathrm{k} + 0 + \mathrm{I}_{\mathrm{yy}} \mathrm{w}_{\mathrm{x}} \mathrm{w}_{\mathrm{y}} \mathrm{k} - \mathrm{I}_{\mathrm{zz}} \mathrm{w}_{\mathrm{x}} \mathrm{w}_{\mathrm{z}} \mathrm{j} - \mathrm{I}_{\mathrm{xx}} \mathrm{w}_{\mathrm{x}} \mathrm{w}_{\mathrm{y}} \mathrm{k} + 0 + \\
&\mathrm{I}_{\mathrm{zz}} \mathrm{w}_{\mathrm{y}} \mathrm{w}_{\mathrm{z}} \mathrm{i} + \mathrm{I}_{\mathrm{xx}} \mathrm{w}_{\mathrm{x}} \mathrm{w}_{\mathrm{z}} \mathrm{j} - \mathrm{I}_{\mathrm{yy}} \mathrm{w}_{\mathrm{y}} \mathrm{w}_{\mathrm{z}} \mathrm{i} + 0; \\
&\dot{\mathrm{L}} = (\mathrm{I}_{\mathrm{xx}} \dot{\mathrm{w}}_{\mathrm{x}} - \mathrm{I}_{\mathrm{yy}} \mathrm{w}_{\mathrm{y}} \mathrm{w}_{\mathrm{z}} + \mathrm{I}_{\mathrm{zz}} \mathrm{w}_{\mathrm{y}} \mathrm{w}_{\mathrm{z}}) \mathrm{i} + (\mathrm{I}_{\mathrm{yy}} \dot{\mathrm{w}}_{\mathrm{y}} - \mathrm{I}_{\mathrm{zz}} \mathrm{w}_{\mathrm{x}} \mathrm{w}_{\mathrm{z}} + \mathrm{I}_{\mathrm{xx}} \mathrm{w}_{\mathrm{x}} \mathrm{w}_{\mathrm{z}}) \mathrm{j} + \\
&(I_{zz} \dot{w}_z - I_{xx} w_x w_y + I_{yy} w_x w_y) \mathbf{k}
\end{aligned}$$

$$
\begin{aligned}
&\dot{L}=(I_{xx}\dot{w}_x+(I_{zz}\text{-}I_{yy})w_y w_z)i+(I_{yy}\dot{w}_y+(I_{xx}\text{-}I_{zz})w_x w_z)j+\\
&(I_{zz}\dot{w}_z+(I_{yy}\text{-}I_{xx})w_x w_y)k;\\
&\text{Euler Equations:}\\
&T_x=I_{xx}\dot{w}_x+(I_{zz}\text{-}I_{yy})w_y w_z\\
&T_y=I_{yy}\dot{w}_y+(I_{xx}\text{-}I_{zz})w_x w_z\\
&T_z=I_{zz}\dot{w}_z+(I_{yy}\text{-}I_{xx})w_x w_y
\end{aligned}
\tag{3.40}
$$

3.5.5. Gyroscopic Action in Machine

The concept of gyroscopic action in machines is explained in Figures 3.15 and 3.16.

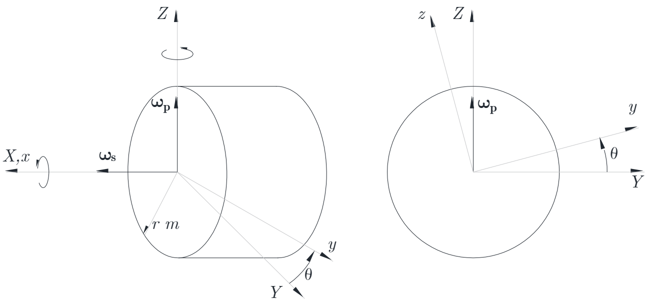


Figure 3.14. Gyroscopic Action in Machines.

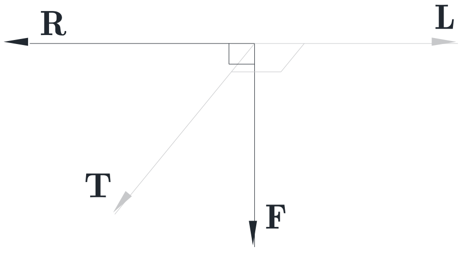


Figure 3.15. Vectors of T, L and F.

The main concept behind the motion of the angular momentum vector, the torque vector T can be chased by angular momentum vector L. The direction of the angular momentum is the same, if there is no external torque. The spin velocity and the inertial properties of the body highly affect the amplitude. When the angular momentum vector L turns 90 degrees in the direction of the precession w_p, the torque vector can be easily determined.

3.4. GYRO-STABILIZER CONTROL

3.4.1. Open Loop Control with Closed Loop

The open-loop control-moment gyro is associated with closed-loop momentum wheel control. In gyro control, the first strategy requires prior knowledge of relocation. Using the Gimbal velocity direction method, the numerical simulation of the control moment gyro (CMG) is performed for a given baseline motion. Using numerical simulations, Gimbal angles, velocities and accelerations can be calculated for the starting angle. The gimbal information is implemented on a yacht in an open loop form. Open-loop CMG maneuvering, no initial state error and complete knowledge of the system force the ship to perform the desired reference operation; however, initial conditional errors, disturbances, or uncertainties in the system parameters can cause the ship to escape the baseline motion. By implementing the law of feedback control on the wheel of the derived impulse, the initial state and disturbance errors can be corrected. The "reference movement" block represents the angular velocity and attitude for the desired maneuver, as shown in control stages illustrated in Figure 4.9. The "system" block represents the angular velocity and behavior of the spacecraft. The output of the system is the difference between the reference and angular velocity and the attitude of the system.

Where:

MW denotes equations that describe the momentum wheels.

I_t and I_s are the transverse and spin inertias of the flywheel.

$\dot{h}_{wa}$ Shows the absolute angular momentum of the flywheel.

$\dot{g}_{w}$ Represents torque that the body acceleration the flywheel.

$\dot{g}_{CMGj}$ Is the torque that the body exerts on the j-th CMG.

h_{swa} Is the absolute angular momentum of the flywheel about the spin axis,

h_{sga} Is the absolute angular momentum of the gimbal frame and the motor about the spin axis.

ω Shows the angular velocity

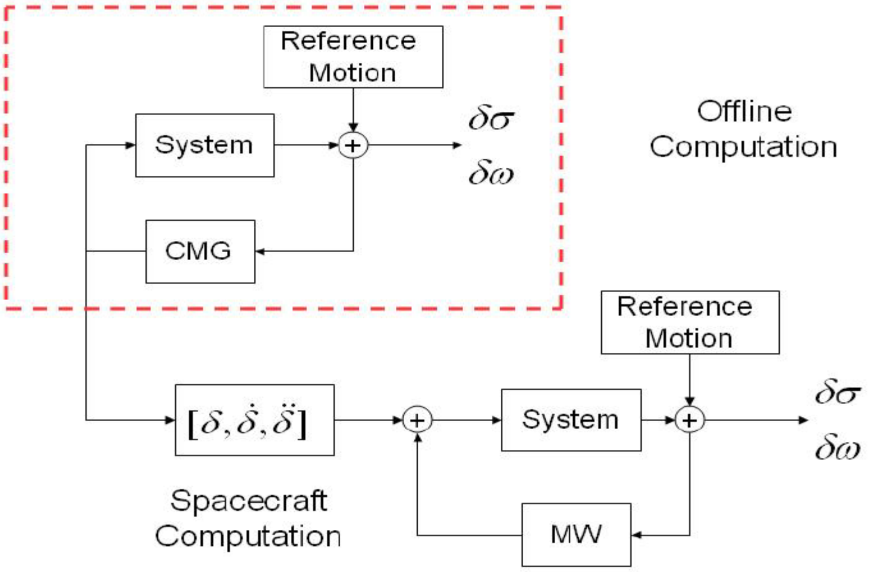


Figure 3.16. Open and Closed-loop Control for CMG and the Momentum wheel.

The CMG gimbals' information in the pre-processed maneuver has been transferred from the open loop to the ship. The feedback control of the impulse wheel compensates for the initial state or tracking error between the reference trajectory and the actual spacecraft. Most of the torque required for the start-up function occurs in the CMG, which is not the case in the drive wheel.

3.4.1.1. Lyapunov Control

Lyapunov control law can be used to minimize errors in the body-fixed reference frame for reference frames. Using Lyapunov's method, the feedback control law is derived as follows:

$$V = \frac{1}{2}\delta\omega^T k_1 \delta\omega + 2k_2 \ln(1 + \delta\sigma^T \delta\sigma) \qquad (3.41)$$

Where:

1. K_1=k_1^T>0
2. K_2>0k1 .. k2 ??

$$
\begin{aligned}
&\dot{V} = \dot{H}^{T} I_B K_1 \delta\omega + K_2 \delta\sigma^T \delta\omega \\
&\dot{H} = -\omega((I_B + A_t I_t A_t^T + A_s I_{sg} A_s^T)\omega + A_s h_{s\omega a} \\
&+A_g h_{ga} + C_s h_{s\omega MWa}) + g_e - I_{B\omega}{}^{X} \delta\omega \\
&-I_B R^{BR} I_B^{-1}[-\omega_R^X T_{\omega R} + g_R] \\
&-\dot{A}_s h_{s\omega a} - A_s g_\omega - C_s g_{MW} \\
&-A_g (diag((I_t - I_s) A_t^T \omega - I_{s\omega}\Omega)(A_t^T \omega) + g_g) \\
&-(\dot{A}_t I_t A_t^T + A_t I_t \dot{A}_t^{T} + \dot{A}_s I_{sg} A_s^T + A_s I_{sg} \dot{A}_s^{T})\omega \\
&-(A_t I_t A_t^T + A_s I_{sg} A_s^T)\dot{\omega}
\end{aligned}
\tag{3.42}
$$

When $\dot{}$H is in the expanded form, we identified the control torques for the system $\mathbf{g_e}$, $\mathbf{g_w}$, $\mathbf{g_g}$, and$\boldsymbol{g_{MW}}$. $\mathbf{A_g}$ is constant, while $\mathbf{A_s}$ and $\mathbf{A_t}$ vary with gimbal angles. In addition, the inertia of the j-th CMG in F_{Gj} can be expressed as diag (I_{sj} ,I_{tj} , I_{gj}) where I_{sj} , I_{tj} , and I_{gj} represent the spin axis inertia, transverse inertia, and gimbal axis inertia, respectively. The external torque of the system is g_e.The spin torque for a CMG maintains a constant velocity of the flywheel about its spin axis relative to the body, which is expressed as:

The g_{MW} has been chosen to control torque:

$$
g_\omega = I_{s\omega}(A_s^T \omega + A_s^T \dot{\omega})
\tag{3.43}
$$

The control torque can be attained as follows:

$$
\begin{aligned}
&C_s h_{s\omega MW} = \delta h - A_s h_{s\omega a} - A_s g_{\omega} - A_g h_{ga} \\
&-(A_t I_t A_t^T + A_s I_{sg} A_s^T)\dot{\omega} \\
&(\dot{A}_t I_t A_t^T + A_t I_t \dot{A}_t^T + \dot{A}_s I_{sg} A_s^T + A_s I_{sg} \dot{A}_s^T)\omega \\
&+k_2 \delta\sigma + k_1 \delta\omega
\end{aligned}
\tag{3.44}
$$

3.4.1.2. Lyapunov Control with Constant Moment

The momentum wheel uses Lyapunov control with constant moment of inertia as an assumption. Normally, the change in inertia in the order of magnitude is smaller than the system inertia for most of the CMG systems. Moreover, the change in the moment of inertia of the system takes place due to CMGs, which is negligible, and it can reduce the amount of computation required by the controller. The equations are given below:

$$
\begin{aligned}
&\delta \dot{\sigma} = G(\delta\sigma)\delta\omega \\
&\delta \dot{\omega} = I_B^{-1}[\delta h - A_s h_{s\omega a} - A_s g_{\omega} - A_g h_{ga} \\
&-(A_t I_t A_t^T + A_s I_{sg} A_s^T)\dot{\omega} - C_s h_{s\omega MW}]
\end{aligned}
\tag{3.45}
$$

Using equation 3.36 to find out the control input:

$$
\begin{aligned}
&C_s g_{MW} = \delta \dot{h} - \dot{A}_s h_{s\omega a} - A_s g_{\omega} - A_g \dot{h}_{ga} \\
&-(A_t I_t A_t^T + A_s I_{sg} A_s^T)\dot{\omega} + k_2 \delta\sigma + k_1 \delta\omega
\end{aligned}
\tag{3.46}
$$

3.4.1.3. Lyapunov Control without Knowledge of the CMGs

The momentum wheel can use Lyapunov control without knowledge of the CMGs. The previous Lyapunov control laws without knowledge of the CMGs saved computation time, as shown in the following equation:

$$
\delta \dot{h} = I_B \delta \dot{\omega} + C_s g_{s\omega MWa} \tag{3.47}
$$

Equation 3.36 transformation is given below:

$$\begin{gathered}
K_1 = K_1^T > 0, \\
K_2 => 0 \\
\dot{V} = \delta\omega^T (\delta \dot{h} - C_s \dot{h}_{s\omega MWa} + k_2 \delta\sigma) \\
If \ : K_1 = I_B \\
C_s g_{MW} = \delta \dot{h} + k_2 \delta\sigma + k_1 \delta\omega
\end{gathered} \tag{3.48}$$

3.4.1.4. Feedback Linearization

The momentum wheel feedback linearization took place. For some types of nonlinear systems, it can use the state feedback control to convert the variables and convert the nonlinear system into a linear system by investigating the input state linearization of this nonlinear system, which is mathematically stated as follows:

$$\begin{gathered}
Z1 = \delta\sigma \\
Z2 = \ ? \\
Z_1 = \delta\omega \\
Z_2 = G(\delta\sigma)\delta\omega = \delta\omega
\end{gathered} \tag{3.49}$$

This can be transformed into the following expressions:

$$\begin{gathered}
\dot{Z}_1 = Z_2 \\
\dot{Z}_2 = \dot{G}\, \delta\omega + G \delta \dot{\omega}
\end{gathered} \tag{3.50}$$

Where:

$$\dot{G} = G(\delta \dot{\sigma})$$

This equation can be written as follows:

$$
\begin{aligned}
&\dot{Z}_1 = Z_2 \\
&Z_2 = \dot{G}\,\delta\omega + G(I_B^{-1}(\delta h - \dot{A}_s h_{s\omega a} - A_s h_{s\omega a} - A_g \dot{h}_{ga} \\
&-(\dot{A}_t I_t A_t^T + A_t I_t \dot{A}_t^T + \dot{A}_s I_{sg} A_s^T + A_s I_{sg} \dot{A}_s^T)\omega \\
&-(A_t I_t A_t^T + A_s I_{sg} A_s^T)\dot{\omega} - C_s g_{MW})
\end{aligned}
\tag{3.51}
$$

It can cancel the nonlinear term by selecting C_{sgMW} in this format; therefore, the momentum wheel control torque can be chosen as follows:

$$
\begin{aligned}
&C_s g_{MW} = \delta h - \dot{A}_s h_{s\omega a} - A_s \dot{h}_{s\omega a} - A_g \dot{h}_{ga} \\
&-(\dot{A}_t I_t A_t^T + A_t I_t \dot{A}_t^T + \dot{A}_s I_{sg} A_s^T + A_s I_{sg} \dot{A}_s^T)\omega \\
&-(A_t I_t A_t^T + A_s I_{sg} A_s^T)\dot{\omega} + I_B^{-1} G^{-1}(\dot{G}\,\delta\omega + v)
\end{aligned}
\tag{3.52}
$$

Where:

$$
v = K_5\delta\sigma + K_6\delta\sigma \tag{3.54}
$$

The system with control torque will be as follows, if the constants K_5 and K_6 are positive.

$$
\dot{Z} = \begin{bmatrix} k_6 & 0 \\ 0 & k_5 G^{-1} \end{bmatrix} Z \tag{3.55}
$$

3.4.1.5. One Open-Loop CMG

The one open-loop CMG and momentum wheel feedback control may consider providing a large torque for a single axis, but the momentum wheel cluster provides the closed-loop attitude control. Since the stability of the closed loop system is a result of the momentum wheel control law, the previously derived closed loop momentum wheel control law can be used in this configuration.

The CMG operation can be selected, so that the output torque of the CMG provides a significant portion of the torque required for tracking. A simple example uses the CMG to provide the torque to the main shaft slew of the spacecraft, while the propulsion wheel corrects the tracking errors.

3.4.2. Closed-Loop Control

The control moment gyro and the momentum wheel provide the closed-loop control. The second control strategy implements both CMG and momentum wheels in closed-loop control. The CMG and momentum wheel control laws in the form of a parallel feedback are shown in Figure 3.22.

Implementing multiple control laws in parallel can inflict undesirable effects on the overall performance. A possible solution to implement the two control laws is using the CMG with the closed-loop control law. Performing an integration step on the error using the CMG helps finding the momentum wheel feed-forward control torque from the predicted error. Figure 3.23 shows a block diagram of the control strategy.

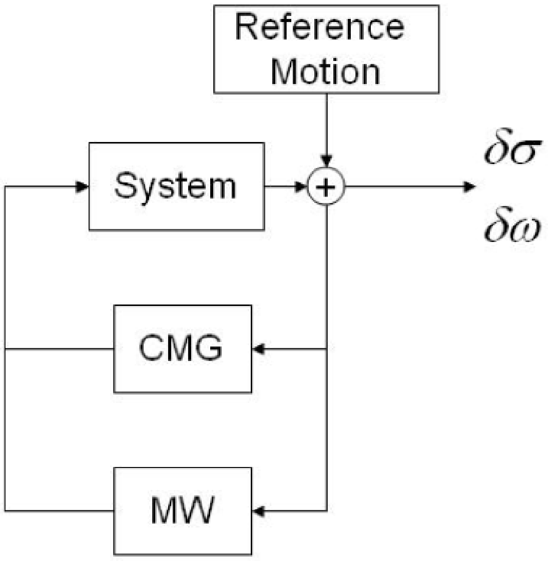


Figure 3.17. The closed control organization for CMG.

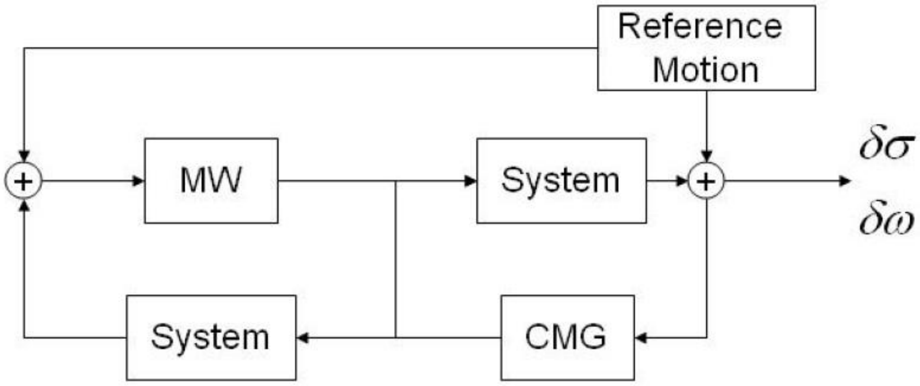


Figure 3.18. Closed loop control organization for the CMG and the momentum wheel.

3.4.2.1. Parallel Control Moment Gyro and Momentum Wheel Control

For a given situation, feedback control on both actuators can be implemented using an error tracker without pre-processing. To reduce the controller calculations, the Lyapunov momentum wheel controller can withhold the knowledge of the CMG. The gimbals ratio steering law and Equation 3.43 are applied in parallel.

$$C_s g_{MW} = \delta \dot{h} + k_2 \delta\sigma + k_1 \delta\omega \tag{3.56}$$

3.4.2.2. Closed Loop Control with Lyapunov Feed Forward

The closed loop control has been applied with the Lyapunov feed forward momentum wheel control with the moment from gyro. Gimbal ratio manipulation is again applied as a state error. For CMG Gimbal Rate, the steering feedback control law generates the control torque to stabilize the system. Every step of the way, the CMG control system advances one step to apply the Euler integration. The momentum wheel torque is calculated to compensate for the prediction error because the Lyapunov control law uses the mentioned prediction error. The momentum wheel torque has been derived from the prediction error and the CMG torque is derived from the current error, which are implemented together.

PART4

RESULTS AND DISCUSSION

4.1. OVERVIEW

Figure 4.1 shows the yacht dimensions, while z-axis goes through the center of the yacht mass. The yacht mass has been displayed as a triangle of interest with a grey central area with side length L. The yacht mass is perpendicular to the plane. When the moment of inertia was calculated, a section of the yacht was chosen, which is shown in a front view in the form of an equilateral triangle. Thus, the calculations performed in this chapter have been carried out by the equilateral triangle shown in Figure 4.1.

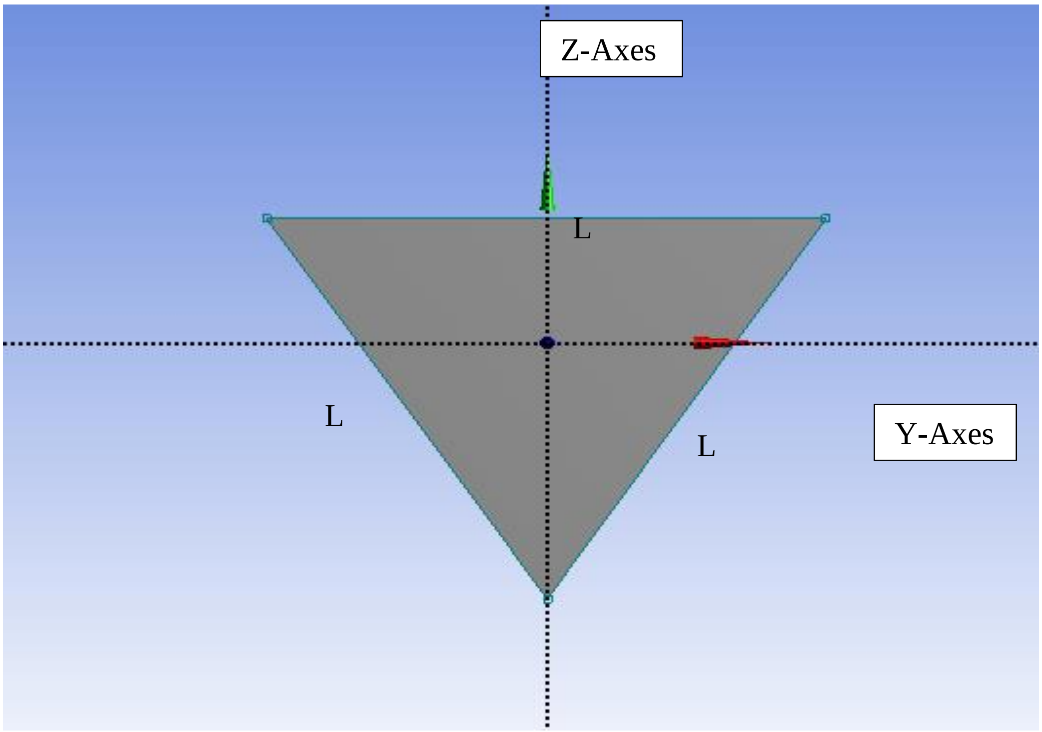


Figure 4.1. Two Dimensions of boot (Yacht).

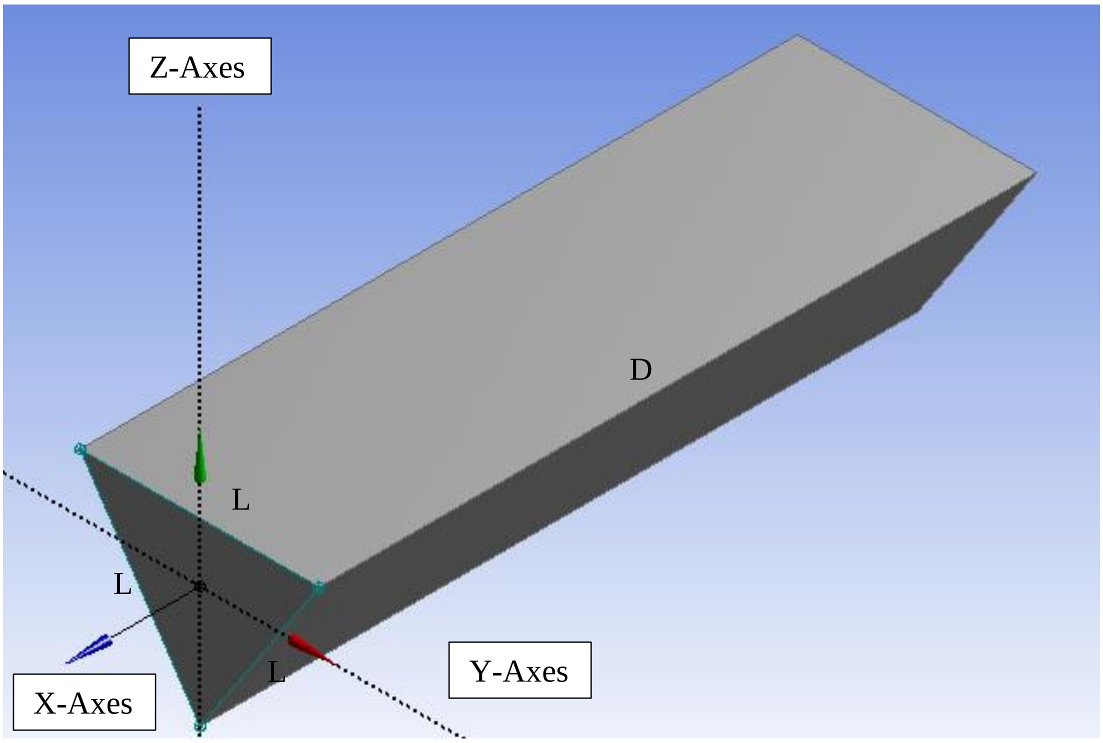


Figure 4.2. Three Dimensions of boot (Yacht).

4.1.1. Gyro Design

The values of different constants and variables of a M70 Gyro framework for a 34-meter motor yacht have been given below:

Moment of inertia *I* = 74.0 kg-m2 for flywheel angular velocity:

ω_F = 250rad/s (approx. 2,400rpm) Angular momentum:

$$\mathbf{L} = I\omega \tag{4.1}$$

$$L = \ 6.7\ (kgm^2)\ \ 1047\ (rad\ /\ s) = 18,500Nms \tag{4.1a}$$

Where **L** is the angular momentum, *I* and ω respectively represent the mass moment of inertia and the angular velocity of the flywheel.

$$L = I\omega F \tag{4.2a}$$

$$\begin{aligned} &= 6.7\ \mathrm{kgm}^2\ \times\ 1047\ \mathrm{rad/s} \\ &= 18{,}500\ \mathrm{Nm}^{-s} \end{aligned} \tag{4.2b}$$

To find out the moment of the inertia with respect to x-axis, the following equation can be used:

$$I_x \ = \mu L^4\ \frac{\sqrt{3}}{48} \tag{4.3}$$

Where I_Z is the moment of the inertia of the x–axis, whileμ is surface mass density, and *L* is the bottom length of an equivalent triangle.

To find out the mass of triangle, Equation 4.4 has been used, where M and *L* are known as M= 10.000kg and L=2m

$$\mathrm{m}{=}\mu \mathrm{L}^2\ \frac{\sqrt{3}}{4} \tag{4.4}$$

Where, *m* is the mass of the triangle and *L* is the side length.

Equation 4.4 is used to find the surface mass density (μ). The outcome is used in Equation 4.3 to determine the torque of inertia along the z-axis (I_Z), as follows:

$$\mathrm{I}_z\ {=}\mu \mathrm{L}^4\ \frac{\sqrt{3}}{48}$$

μ = surface mass density

$$\mu{=}\frac{4\mathrm{m}}{\sqrt{3}\mathrm{L}^2}$$

$$\mu{=}\frac{4.10000}{\sqrt{3}(2)^2}$$

$\mu = 5773 \ {}^{\mathrm{kg}}\!/_{\mathrm{m}^2}$

The average density of the yacht can be determined by using the following equation with yacht length, which is about $D \cong 10m$ and the surface mass density:

$$\rho = \frac{\mu}{D} = 577 \ {}^{\mathrm{kg}}\!/_{\mathrm{m}^3}$$

Where:

1. ρdensity,
2. D yacht length,
3. μ surface mass density

Similar to the torque of the inertia of the z-axis (I_Z), the torque of the inertia of the x-axis (I_x) is determined using the following equation:

$$I_x = 5773.(2)^4 \frac{\sqrt{3}}{48}$$

$$I_x = 3333 \ kgm^2$$

$[\frac{kg}{m^2}].[m^4] = kg.m^2$; unit analysis

Maximum rolling speed rate $\omega_{\mathrm{r}} = \theta_{\mathrm{r}}$ (rad/s)

The angular acceleration α (rad/s^2)

Later, Torque T is calculated using Equation 4.5, as follows:

$$\begin{aligned} T &= I_x \alpha \\ &= 3333.[kgm^2][\frac{rad}{s^2}] = 3333\frac{kgm}{s^2}m \\ T &= 3333Nm \end{aligned} \tag{4.5}$$

Angler momentum is calculated using Equation 4.6 as follows:

$$L = T\,\omega$$
$$L = 3333 Nms \tag{4.6}$$

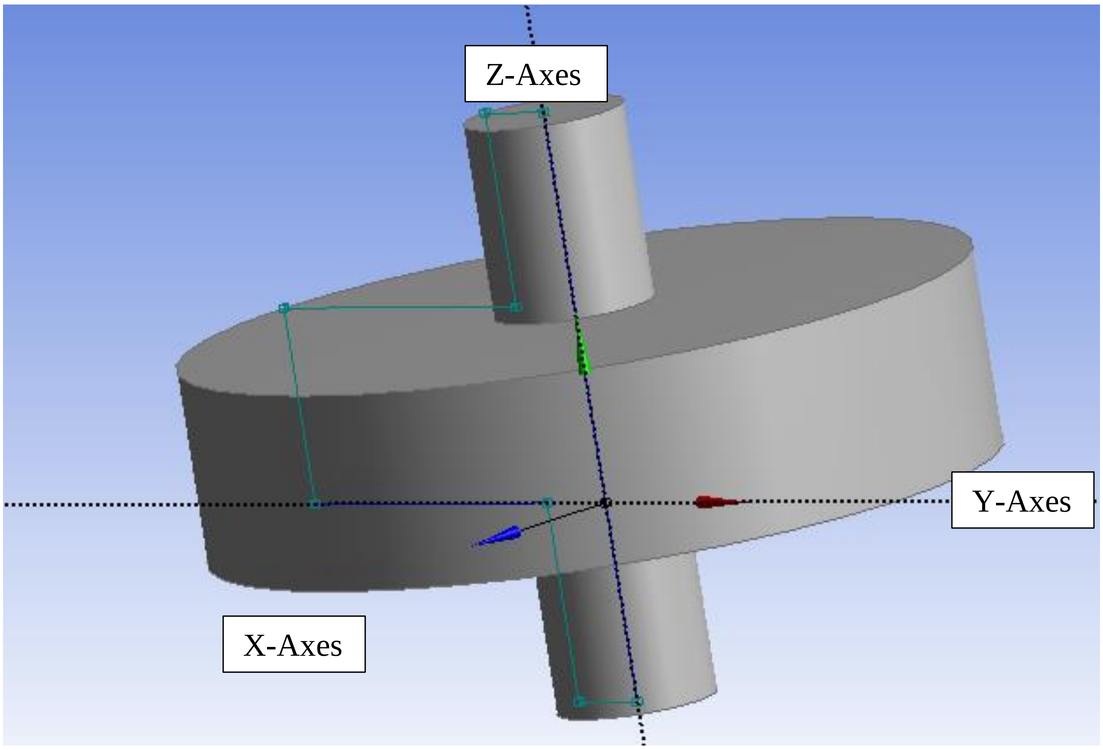


Figure 4.3. The gyro plans.

The output torque of gyro has been calculated using Equation 4.7:

$$T_{gyro} = I_{gyro}\omega_p\omega_s \tag{4.7}$$

Where:

1. I_{gyro} The moment of the inertia of gyro
2. $\omega_s == 732.67\ rad/s\ (7000\ rpm)$
3. $\omega_{P_{max}}$ design criteria $= 0.5\,rad/s$

The relationship between the torque of gyro and the torque of the sea waves has been given as follows:

$$T_{gyro} \cong -T_{wave} = -3333Nm$$

$$T_{gyro} = \frac{T_{gyro}}{\omega_p \omega_s}$$

$$= \frac{3333Nm}{0.5\frac{N}{s}732.67\frac{rad}{s}}$$

$$\cong 9.1kgm^2$$

And,

$$I_{gyro} \cong \frac{1}{2}MR^2$$

$$= 9.1kg.m^2$$

$$\rho_{steel} = 7850kg / m^3$$

The mass of disk is calculated using Equation 4.8:

$$M = P.V \tag{4.8}$$

Where:

1. ρdensity
2. V disk volume

The disk volume is calculated using the following equation and we used it in Equation 4.8 to obtain Equation 4.9, as follows:

$$\begin{aligned} &V = \pi R^2.H \\ &Then, M = \rho \pi R^2.H \end{aligned} \tag{4.9}$$

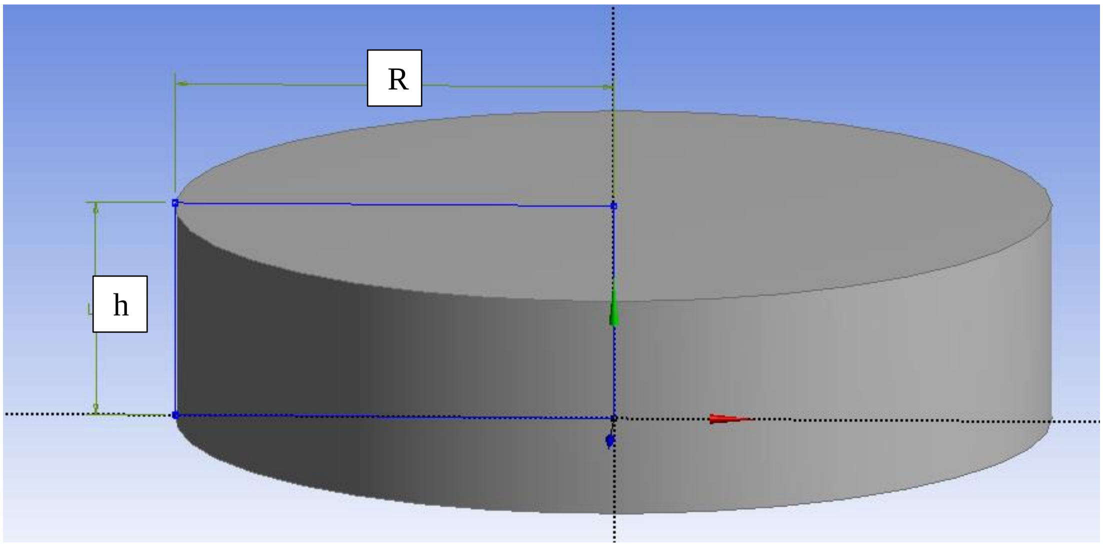


Figure 4.4. The gyro dimensions.

$$\frac{1}{2}p\pi R^{2}h = 9.1$$

$$R = \sqrt{\frac{2.(9.1)}{(7850\pi(0.15))}} = 0.267m = 267mm$$

$$M = \rho\pi R^{2}h = 7850\pi(0.265)^{2}(0.15)$$
$$M = 259.6kg$$

After calculations; the mass of the disk =259.6 kg

The yacht dimensions have been studied, where z-axis passes through the center of the yacht mass. Additionally, the mass of the yacht was studied as a triangle of interest, assuming that the position of gyrostabilizer is at the center of the yacht. Figure 4.5 shows the resulted gyro with final dimensions (x and y-axis), while the radius is 0.265m, h is 0.15m, and the mass of disk is 259.6kg. According to the research calculations, the design gyro will give the best balance to the 10M yacht. Figure 4.6 shows the gyro with the ISO view, while Figure 4.7 shows top view of the resulted gyro.

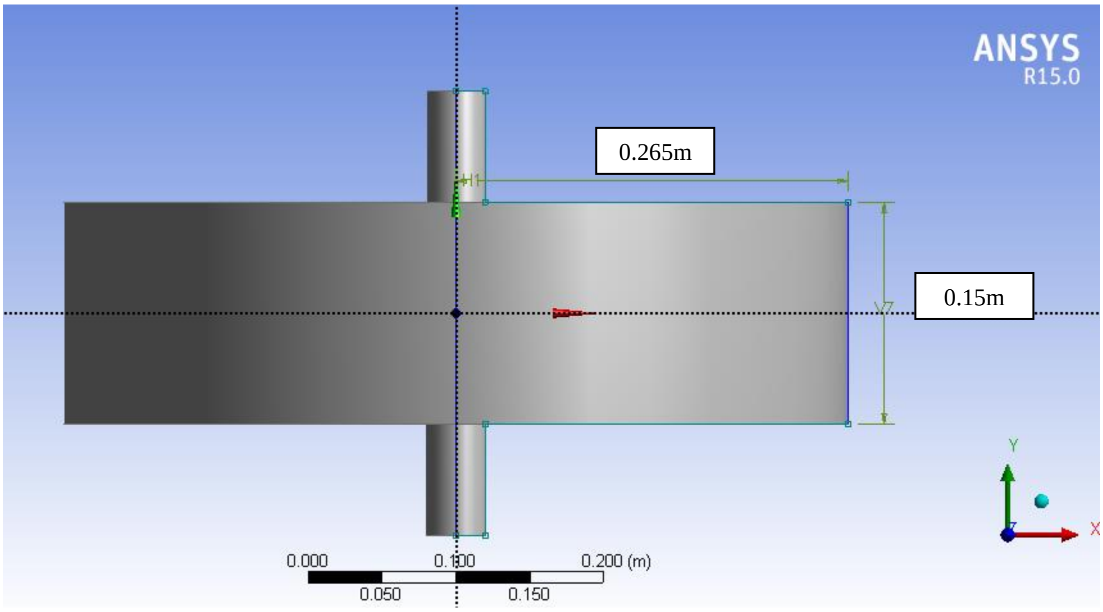


Figure 4.5. The resulted gyro with final dimensions (x and y-axis).

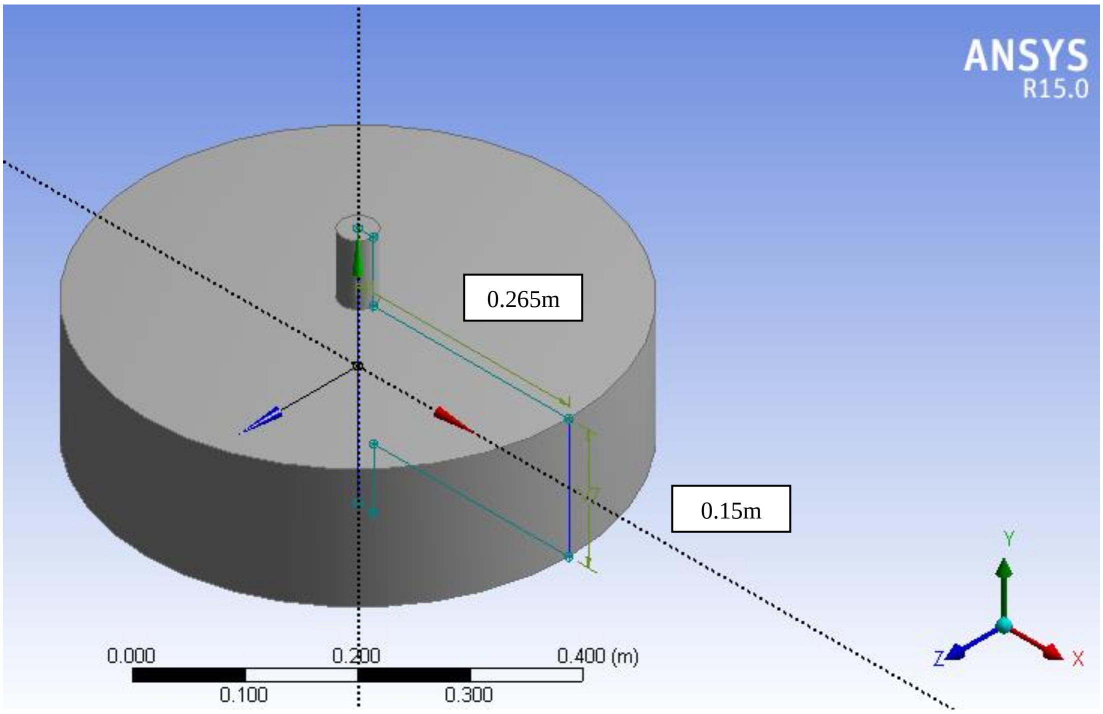


Figure 4.6. Gyro with the ISO view.

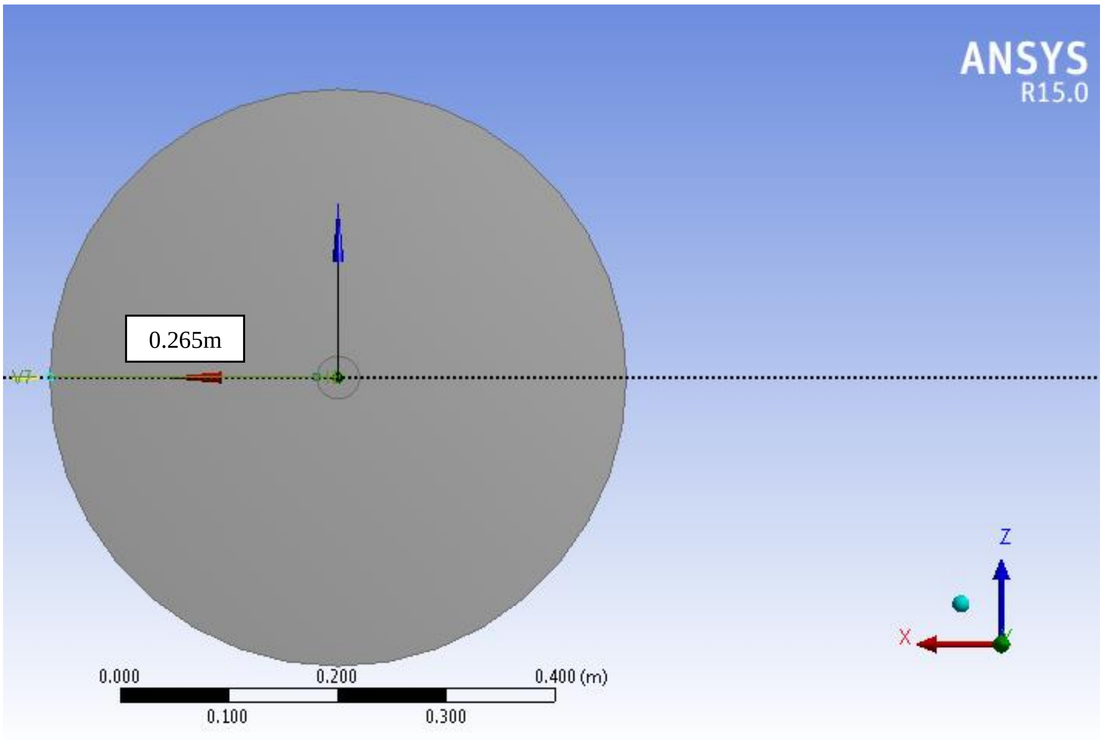
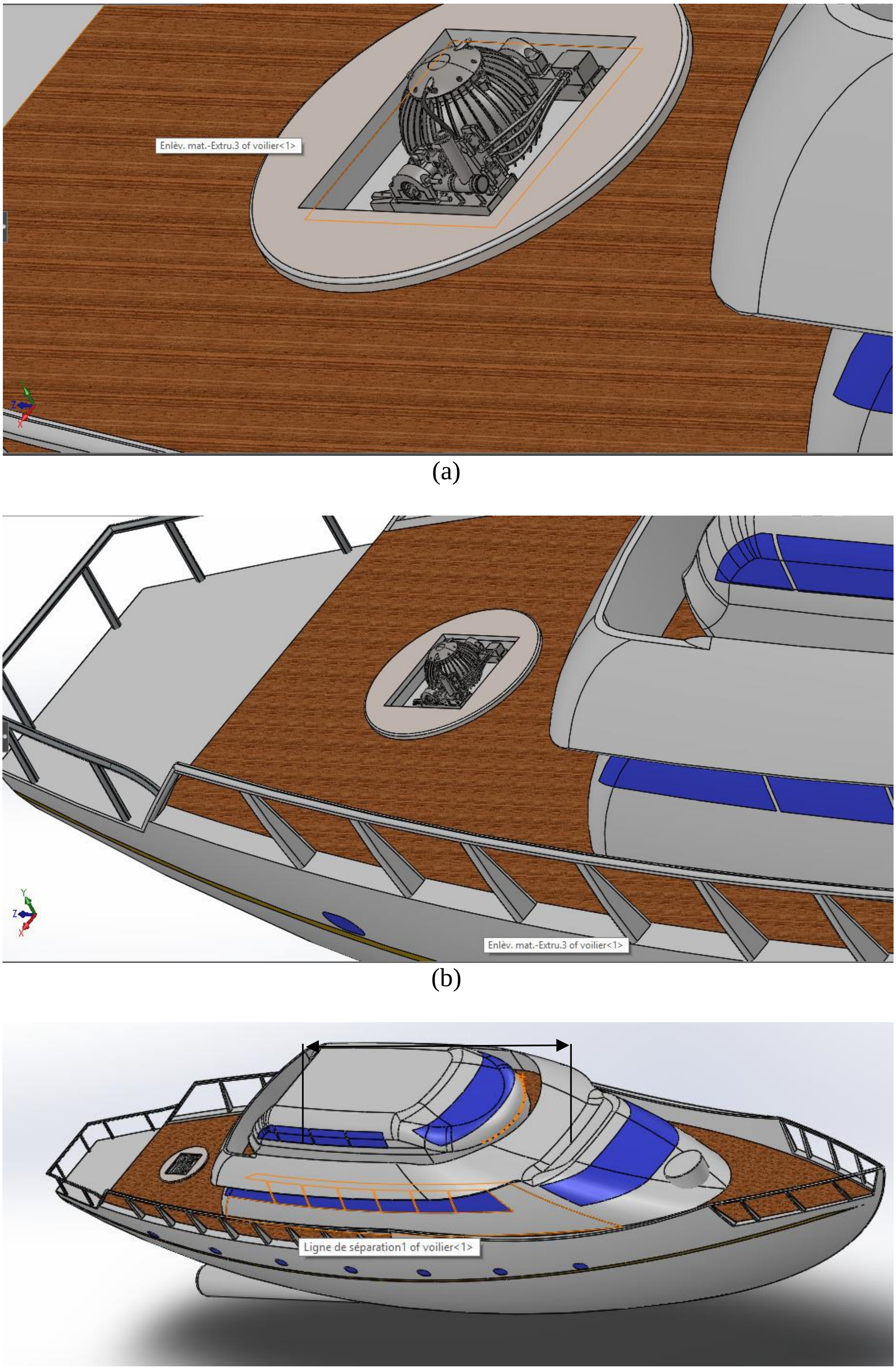


Figure 4.7. Top view of the resulted gyro disk.

Figures 4.8a,b, and c, show sectional views of a control-moment gyro stabilizer, which display its position of installation in a 10-meter yacht with a planning hull. Figure 4.8a shows a top view of the 10-meters yacht, and the expected position of gyro in it. Here “b” shows a side view, and “c” shows the front view of the gyro stabilizer in the yacht. The results show the possibility of implementing a gyro stabilizer in a 10-meter yacht. The gyro stabilizer described in this study has a definitive advantage to the yacht because it stabilizes it at low and high speeds. The presented design is useful also to yachts or boats that spend large amounts of time at low speed, such as coastal patrol boats.



(a)

(b)

(c)

Figure 4.8. a, b, and c: Sectional views of the control moment gyro stabilizer.

PART5

CONCLUSIONS AND RECOMMENDATIONS

5.1. CONCLUSIONS

The aim of this thesis is to study and design a control moment gyrostabilizer (CMG) that can be used in small yachts. The gyro stabilizes the boat using the energy it creates by spinning a flywheel at high revolutions per minute. The research includes the study and design of a device called as a gyro moment stabilizer for a 10-meter yacht, assuming maximum sea wave height as 1 meter. The waves affect the yacht through rolling with a certain force, which creates torque that makes the yacht unsafe and uncomfortable. To deal with this problem, there is a need for a machine or device to stabilize the yacht by producing a counterforce equal to the force produced by the sea waves. The research calculations are based on the Newton's Second Law of Motion. The researcher calculated force, acceleration, moment of inertia and torque. Additionally, all these calculations have been used to find out the gyro specifications and design that are suitable for the assumptions of this case study.

5.2. RECOMMENDATIONS

This research can be extended with further research, following the recommendations given below:

1. It will be helpful to investigate the effect of sea waves, if they have maximum height exceeding 1 meter and its implications on gyro specifications and design.
2. A comparative study between MATLAB calculations and the calculations presented in the current research.
3. Using other ways or methods to find out the gyro specifications and design.

4. Using finite element programs in more researches and comparing the results with real calculation of the gyro specifications and design.
5. Studying the cost factor in optimizing the criteria used in the current investigation.

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APPENDIX A

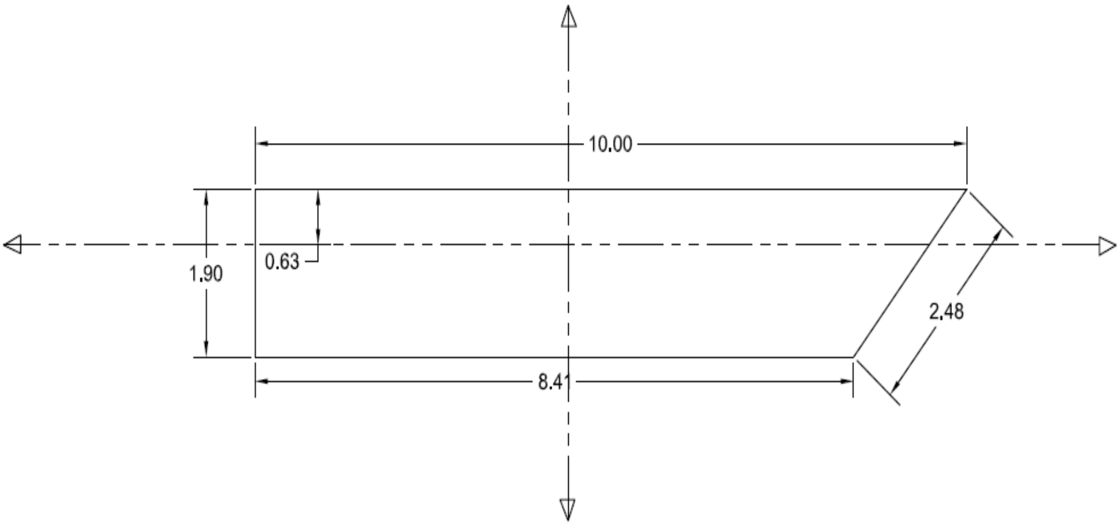

Figure A.1. The side view of yacht.

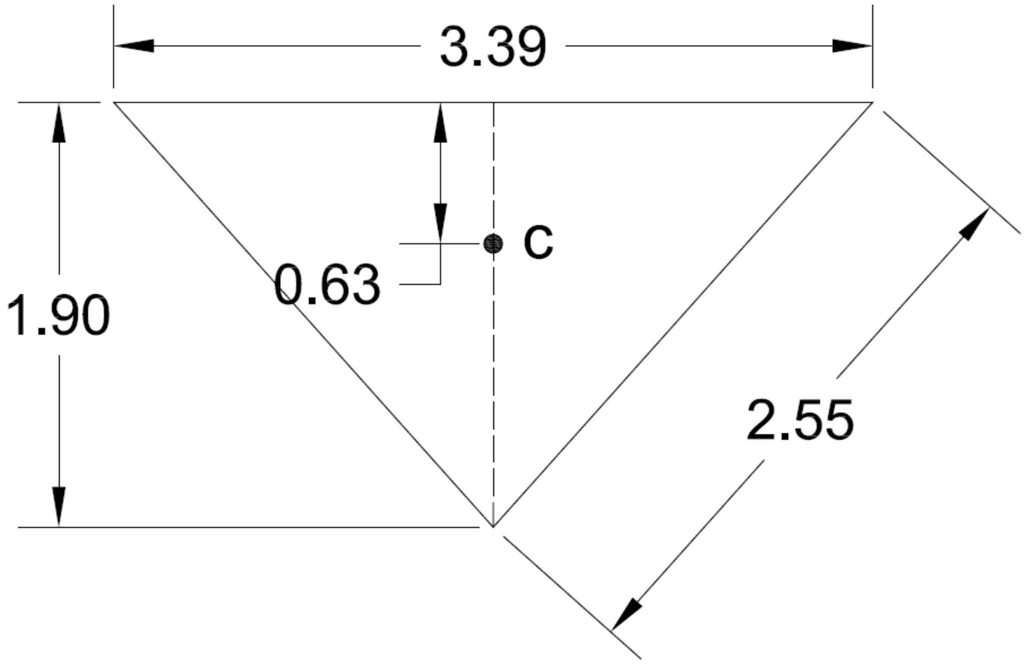

Figure A.2: The dimensions of yacht triangle.

RESUME

I am HUSAM ALASWAD. I was born in Libya in 1982.I graduated elementary, preparatory and high school education in local schools located in my home city: Sabratha. Since I was passionate about learning Marine Sciences, I started my undergraduate studies at the Higher Institute of Marine Sciences Techniques in Sabratha at the Mechanical Engineering Department in 1999/2000, from where, I graduated in 2003. Currently, I am pursuing a master's degree in Mechanical Engineering from Karabük University, Turkey.

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