2022 IEEE 9th International Conference on Underwater System Technology: Theory and Applications (USYS) | 979-8-3503-2313-9/22/$31.00 ©2022 IEEE | DOI: 10.1109/USYS56283.2022.10072471

Multi-Stabilizer Devices for Marine Vessel, Design and Control – A Review

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***Abstract*—Over the years, a new improved technology, mechanisms and systems for marine vessels' stabilization emerge to help improving the condition of crew, cargo or anything on-board that experience the possibilities of being capsized. Referring to marine environment, boat is undeniably subjected to interruption or disturbances from surrounding such as unpredictable waves and strong wind. A variety types of stabilizers are present with different performances based on various kind of control implemented merely to focus on improving the human condition during on-board operation such as berthing, drydocking, loading and unloading or mooring (static) regardless at the inshore or offshore location. Thus, this paper proposes then a review-based discussion of the solutions addressing the issue regarding rolling, including bilge keel, active fin, gyroscopic stabilizer and anti-rolling tank. In addition to this, it could be seen afterwards that none of them could be viewed as the best as for every mechanism they play different role for different ship condition. Though so, it is great to perceive that the existence of new advance technology such as gyrostabilizer is uniquely evolved to remove the extra drag, maintaining the speed of the ship while reducing rolling of the ship..**

***Index Terms*—Anti-Rolling Tank (ART), Anti-Rolling Gyrostabilizer (ARG), Active Fin stabilizer, Bilge keel.**

I. Introduction

In general, boat stabilization is present to ease and comfort people or crew on board. In engineering perspective, those system was particularly there to balance the transverse movement along longitudinal axis which gives high impact on the rolling of the boat, leading to a better marine operation due to high rolling amplitude [1]. Even in real-time marine environment, ship experience motions about 6 degree of freedom concomitantly as shown in Fig. 1 [2]; three translational (surge, sway, heave) and three rotational (roll, pitch, yaw) motion, lots of research had been focusing on only rolling motion as it the most critical motion to ship's stabilization [3] [4]. Over the years, boats have been using bilge keel and active fin stabilizer, but recently, gyroscope have been put into attention. The researches on those devices have becoming more immeasurably extensive recently with the rise of control theory and computational power [5]. It should be a gratitude to Chadwick from mid of 19th century who is the first to design control for ship stabilization through transfer function [6]. In fact, through the implementation of control on systems, the efficiency of the performance could be improved gradually or even dramatically. Regardless the stabilizer, the best rolling removal always dependent on the capability of minimizing the period of the rolling to achieve zero angle, where the ships stay upright. Whilst focusing on the obtaining best stability of boat, seafarer also looks forward to faster speed of their cruise at the same time. Thus, in this paper all discussion upon the four-main design of boat stabilizer which are bilge keel, active fin, anti-rolling tank, and gyroscope will be addressed.

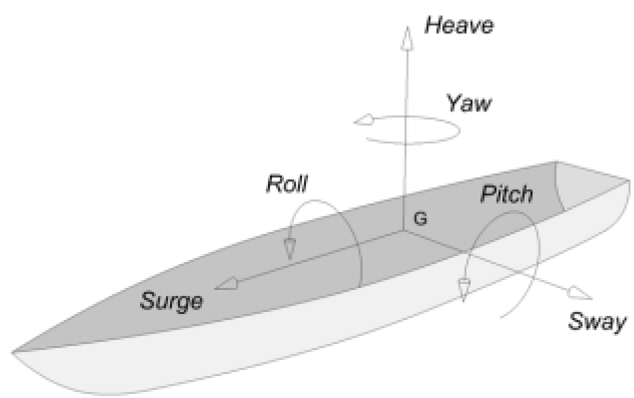


Fig. 1. 6 DOF motion of ship. [2]

High roll amplitude makes any marine operation difficult as it is the most undesirable motion for marine vehicles [3]. In the worst-case scenario, a phenomenon of capsizing may happen causing ruins towards the operation and lots of unwanted losses. Large vessel on the other hand has less fear of being capsized even in heavy rolling [7] as the bigger the vessel is, the higher its durability against the impact waves acting on the body. The vessel density ratio to the sea water density is such a trivial as it experiences higher buoyant force since the wideness of the ship surface area enables the boat volume under the surface displaces the sea water for instance barge structured vessel [8]. Other ways of rolling reduction can be applied through the hull design are reduction of the vertical distance (along the ship's centreline) between the keel and the centre of gravity (KG) or change the mono-hull to catamaran structure [9][10]. Nevertheless, the motion of rolling is still there and might affect the crew's health in terms of seasickness. Hence, here is the role of devices for rolling reduction

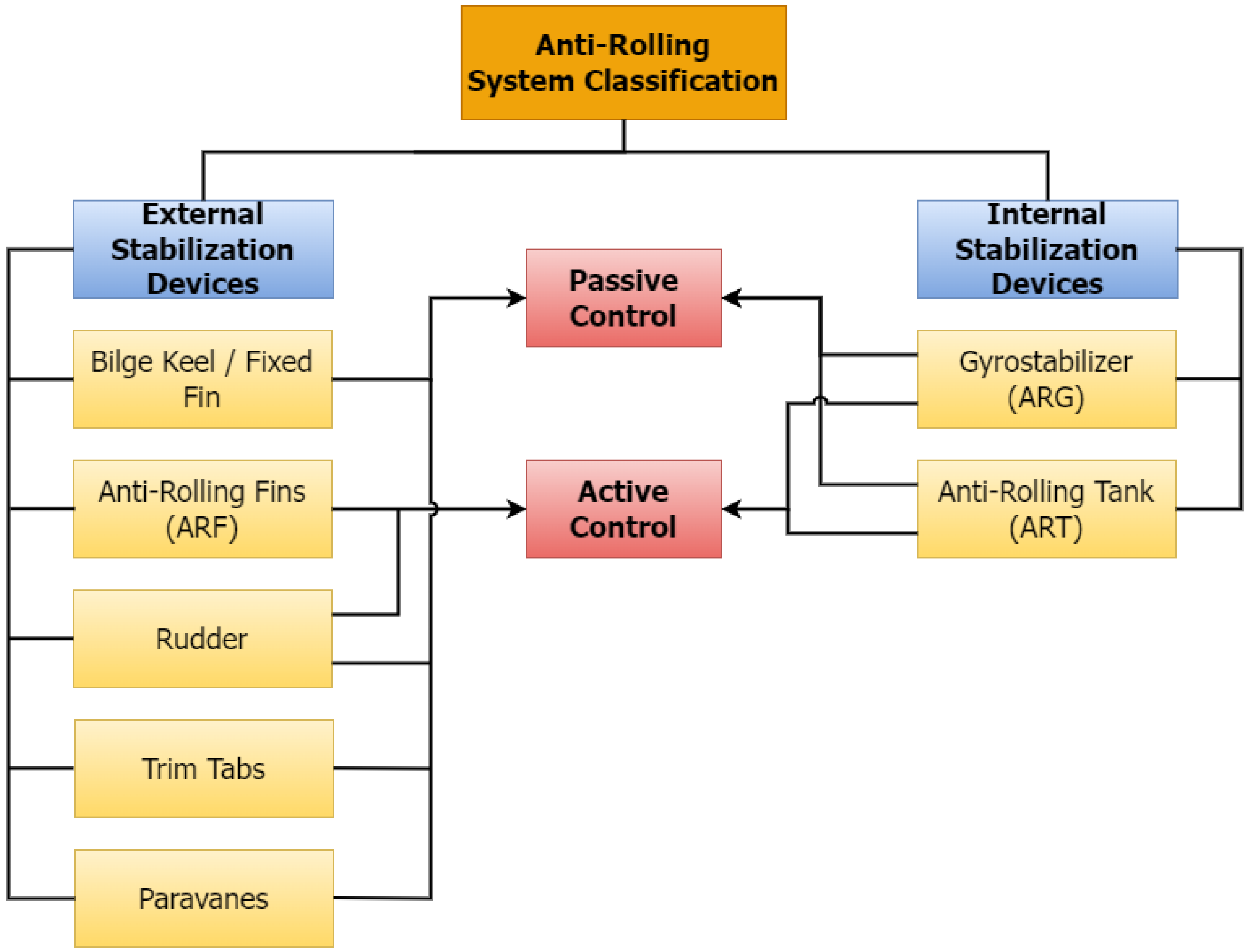


Fig. 2. Classification of Anti-Rolling Stabilizer System.

installed for boat stabilization. It can be classified into two types which are external and internal devices. External device is the mechanism that are installed on the outer part of the yacht or body of the boat. Commonly, it is extending part that is projected such as bilge keel, active fin and rudder. Internal device on the other hand is the opposite, where it does not expose to the outer part of body hull, instead installed on-board or deck. Among those two types of installation, the mechanism could be classified into two classifications which are passively and actively controlled system where active usually requires sensor as observer to monitor the disturbances or change in plant(process) while passive is mainly a natural control-based following the fixed control laws [11]. In other words, passive system uses no separate source of power and no special control while active system is vice versa. All devices for stabilization will be discussed next in this paper based on their design, functionality.

The paper is organized as section one gives a comprehensive introduction of the importance of having stabilizers devices for boat anti-rolling mechanism and their classifications. In the second section, a detailed discussion on various stabilizer devices based on their design construction and control that have been done in the literature. Section three outlines the safety and stability requirement of marine vehicle. Finally, the research prospects and some limitations of previous works.

II. MULTI-STABILIZERS DEVICES FOR MARINE VESSEL

Multiple type of stabilizers exists in the literature, encompassing their variety in classification by types and controls as illustrated in Fig. 2. This section discusses those different stabilizer devices including bilge keel, anti-rolling fin, anti-rolling tank and gyrostabilizer based on their design construction and control. Three types of stabilizers which are rudder control, trim tabs, and paravanes is not discussed for their limited discussion and literature on the vessel's stabilization.

A. Bilge Keel

The Conventional boats have bilge keel as stabilizer mechanism installed on the side of the hull. It is a protruding-like plan or fins that fits externally at bilge curve, commonly at both side, right and left. It is primarily designed to dampen the rolling motion acting on the vessel [12]. The difference between the bilge keel and the fin keel is that the position and its functional. Fin keel is positioned right in the center down the vessel for the purpose of having fast maneuvering or sailing but less stable due to less stable track. Bilge keel on contrast, enables a better directional stability and protection during grounding and greater longitudinal strength at the bilge [12]. Fig. 3 below shows a bilge keel construction of how it is mounted on bilge plate of the boat.

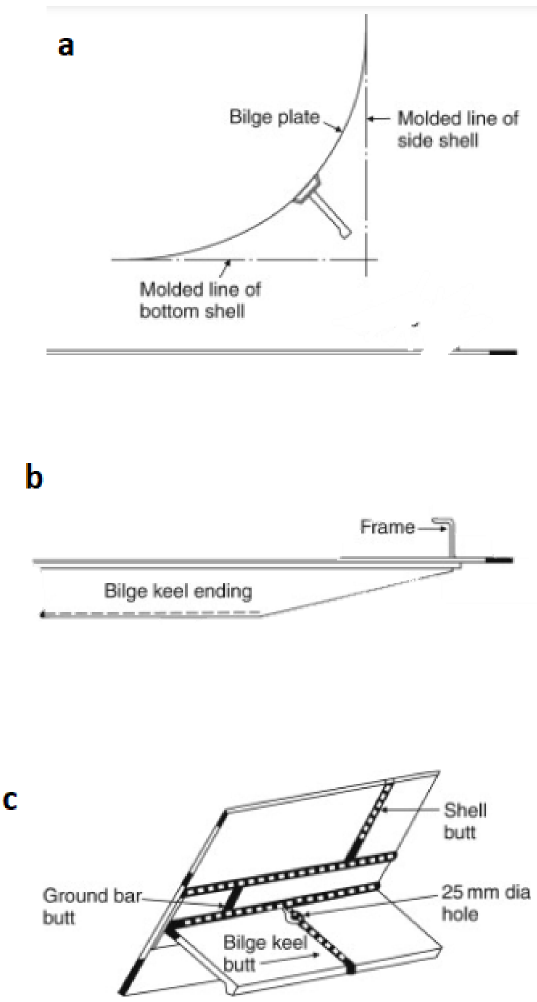
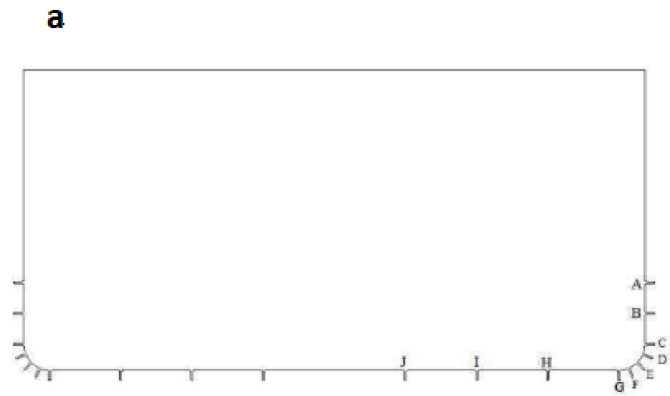


Fig. 3. Construction of bilge keel [12]. a) Front view. b) Side view. c) Perspective view.

Based on its construction, it must be carefully installed so it may not cause excessive drag [12] as well as gives a better performance of damping over rolling. The length of the protruding bilge keel also leads towards some impact for instance, too shallow will give a limited of performance while too deep leads to a possibility of damage during the operation of berthing, drydocking etc [13]. Some study done by few researches on addressing the design and construction of bilge keel towards its performance on boat roll damping has been done. A variation of bilge keel positioned from A-J have been done and observed [14]. Fig. 4 below shows the result.



b

Positions	T_N	ω_N	Kn	b(kgms)
A (1)	1.8546	3.3861	0.0464	0.1818
B (2)	1.8661	3.3653	0.0617	0.2433
C (3)	1.8810	3.3386	0.1530	0.6080
D (4)	1.8748	3.3497	0.2225	0.8813
E (5)	1.8787	3.3428	0.2610	1.0360
F (6)	1.8737	3.3516	0.1850	0.7324
G (7)	1.8723	3.3541	0.1697	0.2790
H (8)	1.8375	3.4176	0.0024	0.0093
I (9)	1.8285	3.4345	0	0
J (10)	1.8276	3.4362	0	0
NO BK	1.6816	3.7345	0.0618	0.2196

Fig. 4. Bilge keel results based on different position across the midships cross-section [14]. (a) Bilge keels distributions at midships cross-section. (b) Results of free decay simulations.

Based on Fig. 4, it is shown that, position E which is 45^0 gives the best damping coefficient, b leading to a better reduction in rolling during a free roll decay test in calm water. It is also agreed that [14] also concluded that the three position of bilge keel tested which are close to the ship keel has none effectiveness at all to dampen the ship roll. This is due to the bilge keel's position does not allow any turbulence by allowing a body of water to flow alongside the boat. Even so, the test is much more to a statically boat at a stance during a halt test not in a movement. Hence, the result might be different in the event of boat sailing in a harsh environment of sea waves for example.

Another exemplary test of bilge keel is on its design, where [15] tested on T-shaped bilge keel performance.

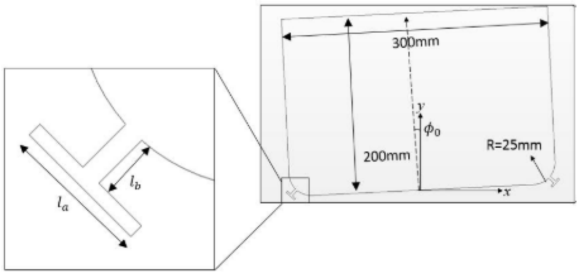


Fig. 5. T-shaped bilge keel. [15]

In the experiment done, they simulated for variation of aspect ratios of T-shaped bilge keels in between 0.5 to 3, length ratio of arms l_a and the body l_b as shown in Fig. 5. The results tested shows a non-linearity in damping coefficient where increasing the aspect ratio does not necessarily in increasing the damping. However, at certain amount of aspect ratio of bigger than 2, they concluded that productive and convincing damping could be achieve. However, a more test should be done as increasing the aspect ratio might cause a detrimental effect on the structural design of the keel itself. Different research has been made previously where changes in vortices of I-type bilge keel is observed on the damping of the boat [16]. Fig. 6 shows the variation made.

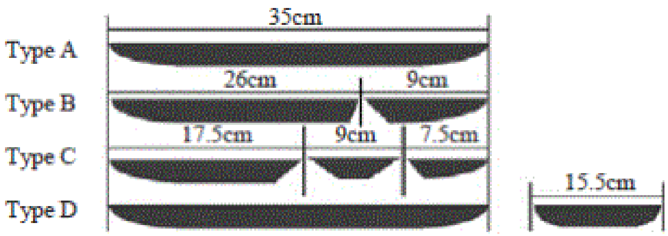


Fig. 6. Different shapes of bilge keel used [16].

Same conclusion can be made as the results shows that type D illustrated the optimal damping while type B and C show bad and insignificant improvement as compared to type A respectively. It is true that more study and experiment shall be done for further improvement of bilge keel development.

B. Active Fin Stabilizer / Anti-Rolling Fin (ARF)

1) Design Construction: Active stabilizer is a protruding mechanism attached on the outer side of the hull body which is electrically or hydraulically controlled, positioned in relation to the water flow that impacts the hull, providing righting the moment of the hull body. From its design, it can be seen that this type of stabilizer is the extension of the bilge keel, except that it is a controlled-based device making it an active system, so as it is named. Fin stabilizer is one of the common anti-rolling device [17] that can be considered in worldwide. In spite of the mechanism, current rapid development of technology allows new device adaptation such as gyrostabilizer, replacing conventional mechanism.

Based on its design, it is very compact and much effective as compared to anti-rolling tank [18] where the tank requires more spaces. It is totally agreed as the fins are external devices which does not affected by internal system except just a spot of space such as installing the actuator for fins control [18]. Some researches emphasized that in theory the fin stabilizers give the highest impact for roll motion mitigation [19]. However, a mere theory shall be proven with real world experiment or bench test to build more confidence to seafarer and mariner since the vessel deals with sea environment complexities that can cause aftermath in roll motion transfer function change [10]. In fact, a fin moving in a fluid is susceptible to drag forces caused by pressure differences and frictional stress, as well as viscous pressure drag, which is vortex drag caused by fluid motion in the boundary layer over the fin surface. Moreover, an additional mass force comes from the certain mass fluid presence during up and down acceleration and deceleration of the fin [20]. These forces demonstrate that there are resistances when using fin stabilizers because of the friction resistance provided by the exposed surface increases, and the residual resistance increases as the hydrodynamic environment surrounding the hull changes [21]. Due to this reason, active fin stabilizer is less effective at low speed [7] and it is dependent on the vessel's speed [18] where the best effectiveness of roll stabilization could be achieved when the ship is at cruise [20].

2) Control: As aforementioned active fin stabilizer is due to ability of the device to be controlled actively. In 2009, a research done to improve parametric roll stabilization through the implementation of combined speed and fin stabilizer control [22]. Parametric rolling happened when a ship is subjected to large roll motion due to increasing in wave height following the head seas. This phenomenon might happen when the wind blows strongly causing the sea wavelength reduced and hence lessen the encounter period. They implement Lyapunov and backstepping control design for forward speed and fin stabilizer control respectively. These controls are compatible when dealing with nonlinear system stability as the complex environment such as waves has the properties of random, nonlinear and unstable [17]. Both controls are in complement of each other as the variation in positive forward speed leads to a larger variation of torque required by the hydraulic actuator to move the fins. Though it is being said that the performance is improved, a larger torque control means a bigger power consumption. Further research shall be made on improving the efficiency of the fin stabilizer performance. Later in 2014, the performance of active fin stabilizer controlled with PMSM (Permanent Magnet Synchronous Motor) drives has been evaluated [18]. In comparison to hydraulics, PMSM increases system efficiency while delivering a more compact design, allowing for more precise control and dynamic performance. From the research, it is found that the higher the boat speed, the lower the inverter output power and the IGBTs power losses. This is because the normal nature of lift forces is reduced at cruise speed [18]. Another improvement made using the PMSM is the fins can be operated as paddle when at low speed instead of as stabilizer in the cruise speed. Fig. 7 below shows the installation configuration of PMSM drive for fin stabilizer control.

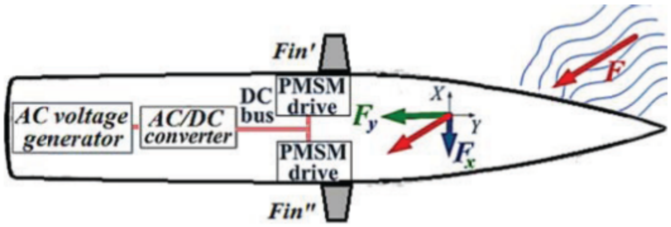


Fig. 7. Fin Stabilizer System [18]

In conjunction to the research, Qi, Jin, Liu and Xu on the other hand manage to simulate the lift model for active fin stabilizer at low forward speed. A clapping fin-like stabilizer was developed with the design fuzzy immune PID controller and implement the simulation on Chinese No.32 fish ship model [20]. Results shown with different encounter wave of 45^0 (quartering seas), 90^0 (beam seas), 135^0 (bow seas) onto the ship body the roll reduction percent manage to achieve up to 70% at 90 degrees and 60% at right angled wave encounter. The result obtained was good enough which is very useful for application such as vessel surveying, surveillance etc. Fig. 8 below shows the definition of seas according to direction of approach relative to vessel.

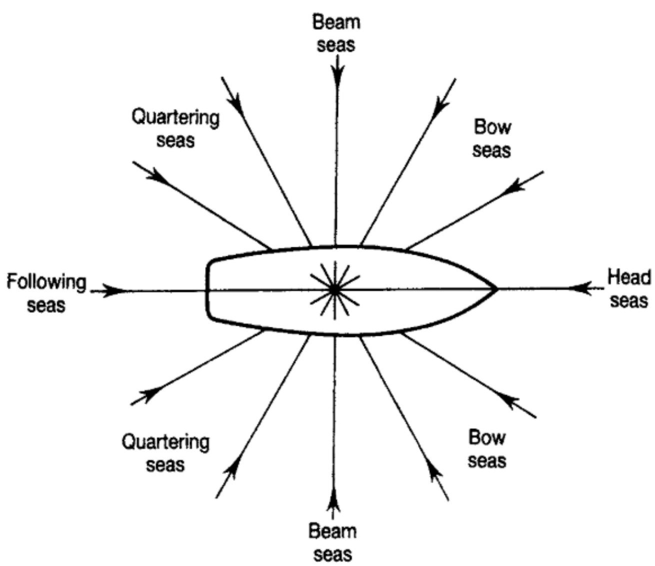


Fig. 8. Wave encounter direction relative to vessel. [23]

In 2017, with a great computational power discovery, intelligent control research has been blended into the current work. Neural network (NN) controller has been presented to enhance the classical PID controller [24]. A comparison test been made which an initial sinking result of ship in unstable transfer function of ship gained a better rolling to be fairly stable with the tuning of NN controller. The researcher also highlighted that the controller is compatible when dealing with change in dynamic parameters of ship such that the dynamic parameters of ship might change due to fuel consumption during operation. Ship's weight varies continuously because fuel and other reserves which are continuously consumed in a sailing ship constitute a major part of its weight.

Next, in 2020 some more advance controller has been introduced on active fin stabilizer. Linear Quadratic Gaussian (LQG) Controller consists of gain regulator obtained from the design Linear Quadratic Regulator (LQR) and gain estimator obtained from the Kalman filter. It has been introduced to improve the roll reduction over LQR controller [17]. Through the contrast simulation done at 3 different wave propagations (45^0,90^0,135^0), LQG can be concluded to be resulting the best performance which reached almost 0-degree roll angle outputs. However, the roll reduction percent did not winded up as per previous research done [20]. Nevertheless, it is indisputably being said that LQG did has better performance over PID controller even PID is the most industry controller [25]. In terms of overshoot, LQG had lower but in terms of settling time, adaptive PID is faster to settle. Apart from that, LQR controller had been specifically tested to reduce roll motion during the turning of ship as upon this movement, the ship undergoes rolling and heeling simultaneously [19]. The result shows that the fin stabilizer controlled with LQR controller has much better improvement during the turning motion experiment in both calm water and under wave disturbance vicinity.

Another type of controller introduced is $H\infty$ is a controller which is compatible in the worst-case scenario. It utilizes one degree of freedom system stabilization. In other words, it is an appropriate control method for ship roll motion caused by disturbance inputs of undetermined amplitude such as dynamic sea states waves. Development of the controller has been done for DTMB 5415 Combatant Warship's active fin stabilizer [10]. The result shows that, the proposed controller manage to reduce over 90% of rolling. However, the experiment was carried out at fixed speed of 30 knot which is quite fast, enabling the possibility of higher stabilization even though the active rolling fin stabilizer serve at its lowest function. This research is undeniably predominant research as it very vexing towards the crew when it comes to parametric rolling, which can result to a bad range of rolling angle, 30-40 degrees. Without control, the crews need to manually increases the speed or change course to prevent the phenomenon.

C. Gyrostabilizer / Anti-Rolling Gyrostabilizer (ARG)

1) Design Construction: Gyrostabilizer or so-called anti-rolling gyrostabilizer uses the principle of conservation of angular momentum [26], where a high-speed spinning disc in an axis is subjected to a motion called gyroscopic precession. This precessional moment is the generated moment from the rotating disc mounted on a frame, enabling to counteract with the force excitation from hydrodynamic waves onto the marine stabilizer, hence stabilizing the hull to stays upright [27]. Fig. 9 below shows the idea of mounting the gyrostabilizer on a vessel.

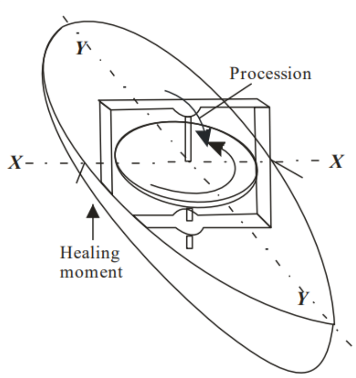


Fig. 9. Installation of the gyrostabilizer on the hull of the vessel. [28]

Another good explanation on gyroscopic stability has been presented by [29], an object that spin has moment inertia, L, along its rotation axis, creating an angular momentum that will always stays constant, unless an external torque is acting on it, leading to change of angular momentum. This statement of Newton's Law of Rotation can be illustrated from below Fig. 10.

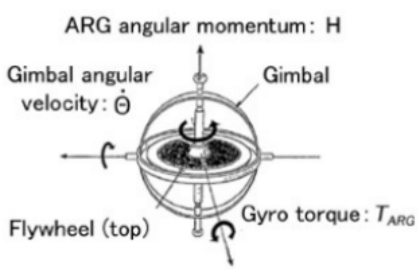


Fig. 10. Working principle of Spinning Gyroscope. [30]

From Fig. 10, it is important to understand that the bigger the gyrostabilizer, the greater the generated momentum and torque [31] for the ease of optimization and size selection of gyrostabilizer based on the boat size. The concept of Newton's Law can be understood from (1):

$$L = I\omega \tag{1}$$

where L is the angular momentum, I is the moment of inertia and ω is the angular velocity. When dealing with a spinning flywheel at high revolution per minute, indicating high speed of rotation, it is very much to believe that the system is costly as it requires uses of motor which is power hungry [30]. Poh et al. [32] also highlighted on the limitations of gyroscope that in the past was due to high costs, intense structural loading, vessel displacement, and insufficient control and maintenance of sailing conditions. Plus, its mechanical strength which were bolted rather than welded at that time, was critically stressed by the high torques causing a severe stress. These difficulties can now be overcome thanks to modern technologies advancing the materials, mechanical criteria, electrical drives enhancement, and control systems which leads to a renewed interest in ship gyrostabilizers [33]. Over the years as the technology evolves, people are looking forward to increase its efficiency by making a controller to create a power saving gyrostabilizer. On the bright side, Townsend and Shenoi [34] present a very scientifically benefits of using the gyrostabilizers such as the system does not add any friction due to hydrodynamic drag. This makes the system impossibly damage from any immersed object for instance seaweed as it does not expose to the rough underwater environment. In addition to this boon, as the system in mechanically installed onboard, it can be maintained productively and needlessly for the vessel to wait for the docking process. Plus, the installation does not exacerbate the ship stability, thus does not worsen the metacentric height of the ship [21]. Another inference done by Demİr [35] that despite its advantages, the volumetric places and weights on the boat are still a disadvantage.

The minimal requirement of gyrostabilizer setup can be observed from any design presented whether in researches or commercialized products. Every gyrostabilizer fixed onto ground, marine or space vehicle are having same basic construction consisting, flywheel rotated with an actuator (high-speed motor), plate as gimbal, and damper [26] [30] as shown in Fig. 11. The system is assembled with nuts and bolts depending on the design fabrication. Gogoi, Nath, Doley, Boruah and Barman [35] highlighted that the necessary condition for the gyrostabilizer on two-wheeler to work is to positioned a little bit on the top side of the body to ensure the centre of gravity (COG) is perfectly stabilized. Same goes to the boat stability analysis [36] [37], installing gyro on a vessel means adding the whole system weight and shifting the centre of gravity (COG) towards the load side. Hence, it is better to add the system above the original vertical distance between the keel and the centre of gravity (along the ship's centerline) (KG) side of the ship for COG is better on the upper side rather than the lower side of the vessel. Equation (2) shows how centre of gravity is shifted and affected with respect to cargo loaded.

$$GG_1 = wd/\omega \tag{2}$$

where GG_1 is the distance by which the COG will shift when cargo (gyro) is loaded, w is the weight of the cargo, d is the change of COG when the cargo loaded, and ω is the total displacement after adding the cargo.

The classification of gyrostabilizer in term of design can be drop down into few types which are based on the number of gyro installed and the flywheel spin axis of orientation. Table I illustrates some types of gyrostabilizers for ship anti-rolling with their orientation type, control type. The flywheel spinning axis and precession motion are parallel with the vessel frame in horizontal spin gyrostabilizer, and vice versa in vertical spin gyrostabilizer. As for number of gyros, it can be made up

TABLE I

DIFFERENT TYPES OF GYROSTABILIZER TYPES AND CLASSIFICATION WITH THEIR SPECIFICATION ON DIFFERENT VESSELS.

Reference	Environment	Vehicle	Type/Classification				Commercial	Real-time Results	Simulation Results
			No. of Gyro	Spin Axis	Orientation	Control			
[26]	Ground	Two-wheeled	Uniaxial/One	Vertical	-	Passive	N	Y	Y
[4]	Amphibious (Ground-Water)	Two-wheeled	Biaxial/Two	Vertical	Parallel	Active	N	Y	Y
[39]	Water	Yacht	Uniaxial/One	Vertical	-	Active	Y (Veem)	N	N
[40]	Water	Yachts (Ferretti 731)	Uniaxial/One	Vertical	-	Passive	Y (Mitsubishi)	Y	Y
[41]	Water	Yacht	Uniaxial/One	Vertical	-	Active	Y (Seakeeper)	N	N
[34]	Water	Ship	Twin-gyro/ Two	Horizontal	Parallel	Active	Y (Ship Dynamics)	N	N
[42]	Water (Regular and Irregular wave)	Scaled 1:50 Barge with static Owt	Uniaxial/One	Vertical	-	Active (PD)	N	Y	Y
[31]	Water (Irregular wave)	Vessel	Biaxial	Vertical	Parallel	Active (H ∞)	N	N	Y
[28]	Water (Regular and Irregular wave)	MV Ofure (Search and Rescue Boat)	Uniaxial/One	Vertical	-	Active	Y (Veem VG145SD)	Y	N
[33]	Water	Naval Patrol Vessel	Biaxial	Vertical	Parallel	-	Y (Halcyon)	N	Y
[37] [43]	Water	Italian luxury Liner	Three	-	-	Active	-	N	N
[30]	Water	Vessel	Uniaxial	Horizontal	-	Active (Fuzzy-tuned PID)	N	N	Y
[44]	Water	Port salvage tug	Uniaxial	Horizontal	-	Active (Adaptive)	N	N	Y

of a single rotatable disc or numerous nested discs mounted on axes [35]. Even so, [38] pointed out that the gyro can be installed more than one (uniaxial) but the outcome for three perpendicular gyroscopes for instance only capable of stabilizing one. On contrary, twin gyroscope attached parallel to each other where their spinning and precession angle are rotating opposing one another are able to remove the effect of gyroscopic moments occur in other direction which are pitch and yaw motion of ship [38].

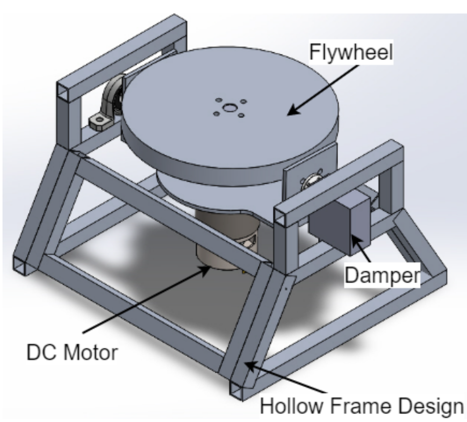


Fig. 11. Single-axis gyrostabilizer.

Townsend and Shenoi [34] presents another good portrayal of single gimbal gyrostabilizer arrangements in Fig. 12, that can geometrically be classified as 'parallel' or 'nonparallel' based on symmetries with respect to their axis of rotation. It is rarely to see non-parallel orientation in the literature as it might be due to imbalance of output torque generated if there is error such as misalignment in arrangement.

2) Control: In term of control, gyrostabilizer can be divided into two main types of control. The first one is passive control which the precession is in free motion rotating about the gyro gimbal axis [31]. The other one actively controlled anti-rolling gyrostabilizer that applies gimbal motor to counter torque of the wave-induced rolling motion at the gimbal frame. The purpose of active controller always to improve the gyro settling time for roll stabilization so that it could achieve faster response even at zero-speed of the vessel [45]. Passive control just literally dependent on the actuator speed of rotation but can never adapt to the complex wave environment with variety of wave-induced amplitude.

Asghar, Talha and Kim [30] demonstrate fuzzy-tuned PID controller for simulation and make a comparison to fuzzy and PID controller separately. The controller measures the hull roll angle and roll angular velocity and feedback the measurement error to the controller to control the gimbal angle and angular velocity to counter torque the wave-induced motion. The precession of the gimbal happens to be limited to $\pm 70^0$ in the vessel pitching's axis. It is observed that the

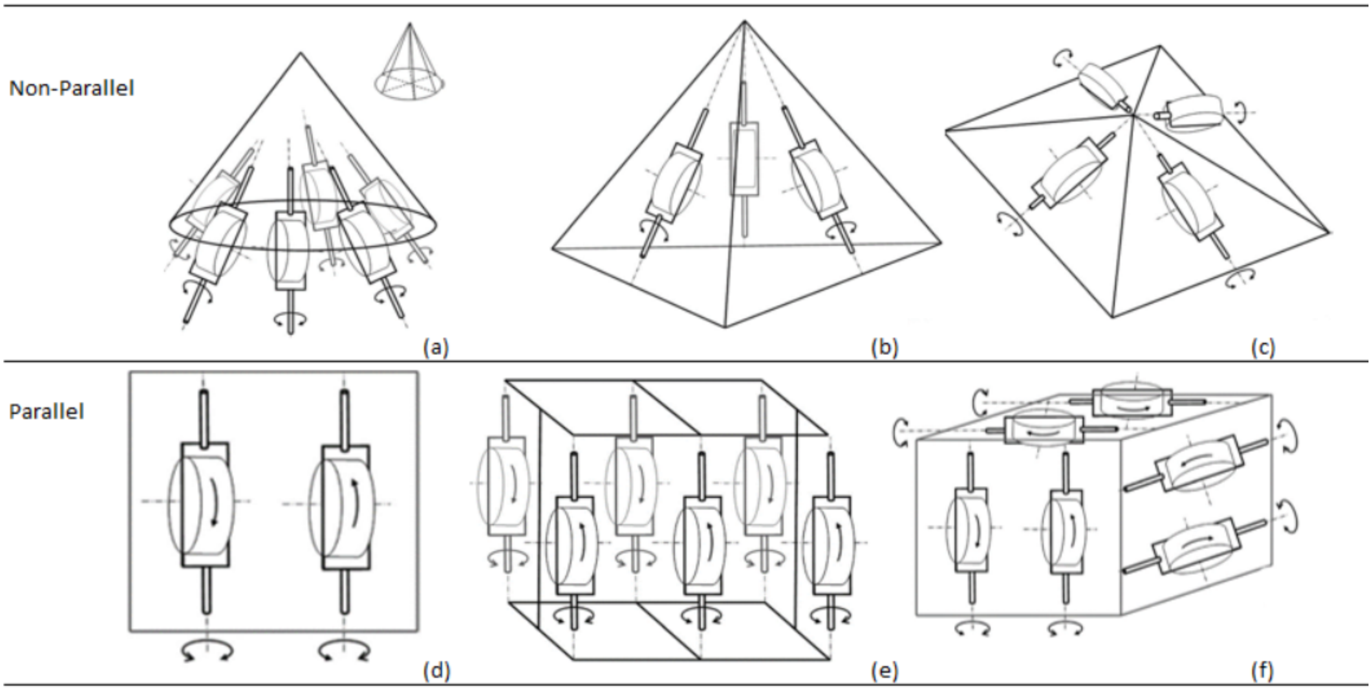


Fig. 12. Single gimbal gyrostabilizer with non-parallel arrangements (a)-(c) and parallel arrangements (d)-(f); (a) Skew arrangement (b) 3 gyro-arrangement (c) 4 gyro-arrangement (d) Twin-type (e) Multiple twin type (1 axis) (f) Multiple twin type (3 axis).

PID controller has problem with its fix gains, leading to the initial fluctuation for stabilizing rolling motion which is not good for crew on-board, whilst fuzzy logic controller do help reducing initial oscillations, but the ship's roll angle settling period is relatively long. This is the reason for the proposed fuzzy-tuned PID controller.

Next, a constrained H∞ control implements in the context of linear matric inequality (LMI) optimization and multiobjective control has been proposed for gyrostabilizer for vessel [31]. The control restricts the precession angle within certain limits and measure the roll angle reduction of the vessel relative to wave. While running the numerical simulation on the research also compares the H∞ with passive control gyrostabilizer and observed that the roll motion reduction performance increase from 77% to 95% respectively in the irregular wave disturbance input of low frequencies as well as at the natural frequency of the vessel.

An adaptive controller type gyrostabilizer based on variable gain control strategy has been presented on a port salvage tug type of ship [44]. The research implements the control on the flywheel precession output moment to overcome wave excitation force and reduce the roll amplitude of ship. The good thing about adaptive controller is that it enables an automated adaptation to the different in roll amplitude of the ship due to the differs in the wave amplitude in irregular undesirable environment. The performance shows that with the rated flywheel spin rate of 2000rpm, the system manages to reach average anti-roll rate of 64.2% with significant wave height of 1.5m and angle of attack of 90^0. Some other control done in the literature with its performance can be observed in Table I earlier.

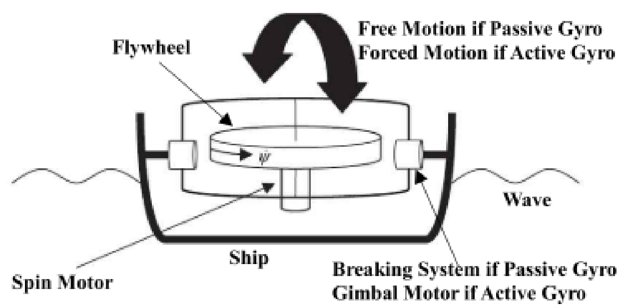


Fig. 13. Operational Principle of Passive/Active Gyro-stabilizer for Ship Motion Control. [46]

D. Anti-Rolling Tank (ART)

1) Design Construction: Anti-rolling tank system is much known as moving weight system. It is usually developed to encounter rolling while at low or zero speed [5]. It is an internal system as per gyroscope but have a few differences in the way it works and the effect on the vessel. The general concept of anti-rolling tank can be conceived as a ship which is internally installed with a tank-like across its transverse axis symmetrically [18], the liquid flow inside it move freely depending on the control applied to change the position of centre of gravity. In another perspective, upon the ship's list, the system shall detect the angle of list, and correct them making the ship upright back to its initial static equilibrium

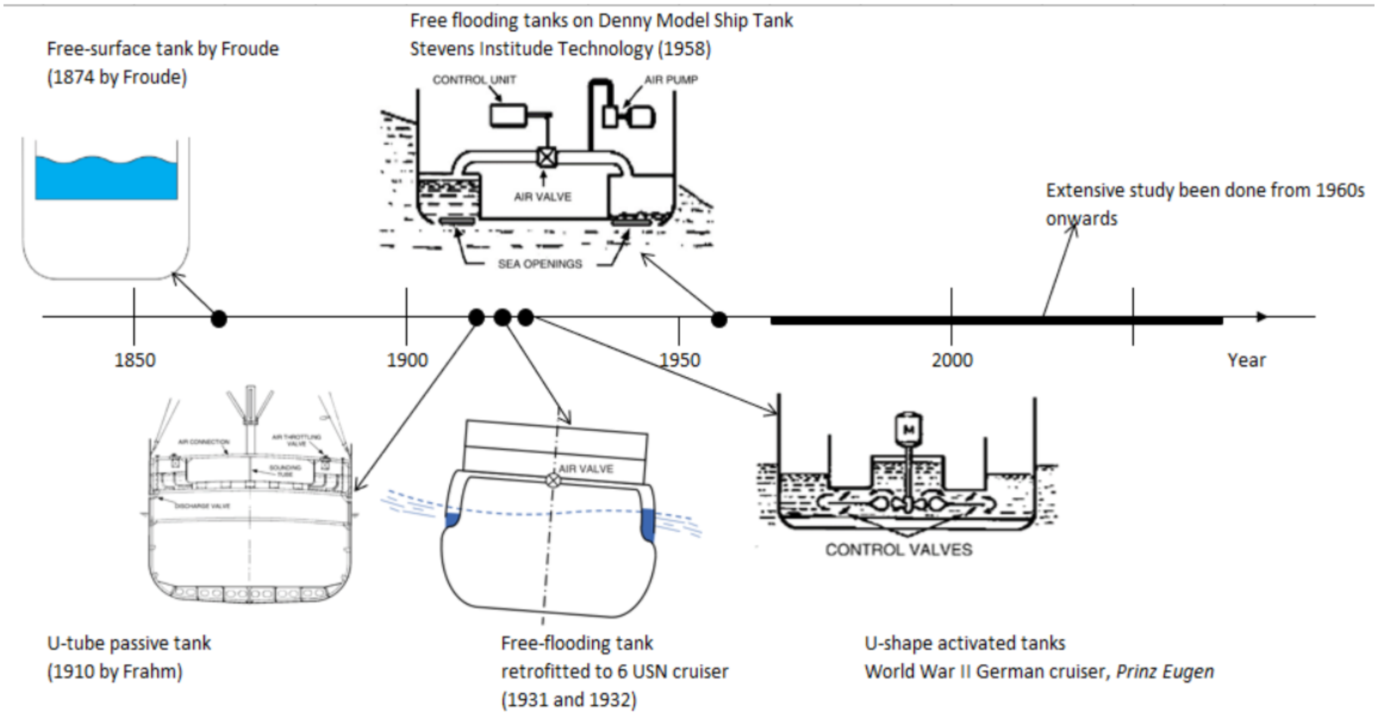


Fig. 14. Development of Anti-Rolling Tank based on History

where the centre of gravity is in vertical line with the centre of buoyancy by moving the fluid across from the listing side to the other side. There are a lot of anti-rolling tank were design since the first developed in the late 18's, the free surface tank by Watts in 1883 for instances U-tube shaped tank, free-flooding tanks and n-tanks [7]. Fig. 14 above shows an illustration and the progress development since its early development of free-surface tank.

Free-surface tank is the simplest system that is very dependent on the natural frequency of the ship rolling to achieve highest efficiency in reducing he rolling. Plus, it is very difficult to control the water and easier for sloshing of liquid to happen inside the tank, reducing its efficiency for anti-rolling [47]. Hence, designing an arbitrary tank shape by adding baffle inside the tank or altering the water level might be able to increase its efficiency. Later than, Frahm in 1911 suggested U–tank system and it solves many of the problems of Watts' simple free surface tank [7]. It is observed passively that the tank gives 50% roll reduction on ships with small metacentric height but not in irregular sea wave condition. The design of passive was later improved to U-shape activated tanks where a turbine-driven blower is installed to pressure the water to be transferred from one side of the to the other. This type of tanks has been installed on German cruiser, Prinz Eugen during World War II. Another installation of activated has been done in 1938 to USS Hamilton [48].

Lastly, the free-flooding tanks developed with the modification from the Frahm initial design where the bottom of the tank were removed and opened to the sea [7]. An improved version of free-flooding tanks on the Denny Model Ship Tank where at the very bottom of the ship have tanks that are opened to the sea, while a valve to open and close is present in the middle of interconnected pipe between left and side of the tank to enable water trapping and discharging for stabilization.

Despite the state-of-the-art of the moving fluid system, the structure has time delay in order to balance the ship in relative to the wave frequencies excited on the body of vessel to be detected. Due to advances in control theory and computational power in late past century and early twentieth century, this considerable slow response time has been studied to be improved. One of the way to solve this is by implementing control like predictive and adaptive as presented by [5]. Apart from that, some research agreed that using the tank system take some large spaces of the ship's deck.

2) Control: It is agreed that active anti-rolling tank (ART) is much effective compared to the passive ART as passive ART is very restricted with the fundamental of having both tank and ship to be synchronized in frequency with the wave for a good stabilization [49] [50]. Based on Marzouk and Nayfeh [47], even it can be seen that active requires more control to be implemented, it is much viable for the active system since the system will seamlessly working even the natural frequency of the ship and the waves is different. Active tanks are capable of generating larger stabilizing moments from the same tank volumes [1] by forcing the flow of liquid from one side of ship to another side (either starboard or port side) by the action of actuator [1] [18]. An actuator such hydraulic motor driving the axial flow pump is one way to provide faster reaction time for immediate response of roll stabilization [7]. However, the higher the flow rate of water transferred, the bigger the amount of resultant power. Fig. 15 below represents active ART system which differs from passive ART system which is the presence and absence of pump power, W dot. Though knowing a good side of active tanks, there is not vast literature conferred.

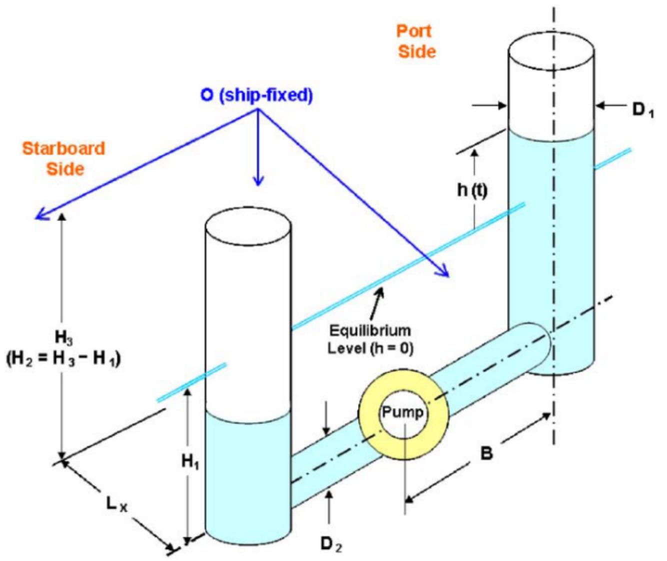


Fig. 15. Design of an Active Anti-Rolling Tank (ART) [47]

A research of passive and active control ART system based on the variation frequency response (FR) and mass ratio (MR) with respect to diameter of the legs, D1 and diameter of horizontal duct, D2 has been investigated. It has been found that, active systems achieve better roll reduction than passive systems of equal mass. A passive ART system with MR=2.1%, reduces roll to 24.9% of uncontrolled value in quartering wave encountering angle and 6.7% at head wave encountering angle. When we turned on the pumps, we discovered that the reduced roll was 1.9%, and 0.21%, respectively. Based on the simulation, an active ART system that is smaller in design can achieve same roll reduction than a passive system. Plus, active ART systems perform less sensitively to their natural frequencies than passive systems enabling the possibilities of stabilizing the ship at irregular wave encounter.

A novel control strategy has been illustrated using predictive control strategy [51] on the ship's anti-rolling tank by varying the air duct in order that the fluid flow could be altered with the varying of wave disturbance frequency. Instead, being actively-controlled, it is passively-controlled tank that has a wider range of adjustability of valve opening. In the research done, a comparison of intermittent flow control strategy that utilizes passively PD control strategy with continuous flow control strategy that utilizes predictive control strategy has been made. Since in the intermittent flow control strategy opens and closes the valve fully based on wave frequency, it happens to be at detrimental disadvantage in long term uses, leading to a faster wear and tear of the valve. On the other hand, continuous flow control strategy, opens and closes the valve size at adjustable range smoothly even the ship's natural frequency is close to the largest wave disturbance frequency. At the two different heights of irregular wave, 3m and 6m, continuous flow control gives a better performance in roll reduction while intermittent flow control only gives a good result at 6m of wave height, not at 3m. The research concluded that the pre-requisite to implement the control is by ensuring that the tank's natural frequency to be higher than the ship's natural frequency, which the valve opening should be sufficient in size for moving the fluid either from starboard to the port side or vice versa.

Moaleji [5] highlighted that a better approach for ART is to apply feedforward control instead of feedback control. Hence, in the research an auto regression method which is used to predict wave motion and adaptive inverse controller with a filtered-x least mean square algorithm has been studied. The pump system receives the projected wave motion as an input in the first method while the controller is implemented at the actuating pumps of an active U-tank. Using the idea of "The moment produced by the waves is proportional to the wave height", the moment created by the waves is monitored and recorded over time, and an Auto regressive (AR) model of the waves is created, capable of predicting the incoming waves with its height for a few seconds ahead. Thus, the wave frequency can be predicted and the amount pump to force the fluid could be pre-determined so that the frequency of ship and tank is synchronized with the waves [49]. For the second approach, it was demonstrated that a filtered-x inverse controller can achieve roll reduction while consuming minimal power and keeping water level variations within a narrow range. However, some challenges highlighted by the authors related to marine engineering where:

- The tank-pump system is very difficult to model and requires in-depth research in the field of fluid mechanics
- Different weather leads to a changing in transfer function of the ship
- Complexity of irregular and random sea waves is a very disturbing noise in nature, leading to a complexity in control system.

III. SAFETY AND STABILITY ASPECT OF ANTI-ROLLING STABILIZER

In stability analysis there are a lot of aspects shall be put into consideration for a ship can be categorized as stable. One of the aspects is the Righting lever (GZ) curve, a graphical representation of the ship's transverse statistical stability. The most important thing in maintaining the ship's stability always reflected on the geometry of the hull and followed by the centre of the gravity after the vessel loaded [55].

Based on the [36] regarding GZ curve shown in Fig. 16, there are characteristics needed to be in examined in order to define the stability owned in a vessel such that:

- At the start is a slope. The righting lever is proportional to the angle of inclination for small angles of heel because the metacentre is essentially a fixed location. Therefore, the metacentric height is represented by the GZ curve's tangent at the origin.

TABLE II
GENERAL COMPARISON ON MULTI-STABILIZERS ON ITS ADVANTAGE AND DISADVANTAGES.

System	Installation	Advantage	Disadvantage
Gyrostabilizer	Internal	1. Compact internal system with no hydrodynamic drag and effective at zero forward speed. 2. Capable of stabilize motion in short interval time.	1. Sometimes require bigger weight and space depend on the vessel size. 2. High speed might endanger crew.
Anti-Rolling Tank	Internal	No hydrodynamic drag and effective at zero speed.	Has time lags due toaction of water flow from one side of tank to another during pump.
Active Fins, **Bilge Keels**, **Rudder Control** [52]	External	Lightweight and unused of internal space, increasing ability for more load onboard.	Exposed to hydrodynamic drag, ineffective at zero speed, vulnerable to physical damage such as seaweed, reef and coral.

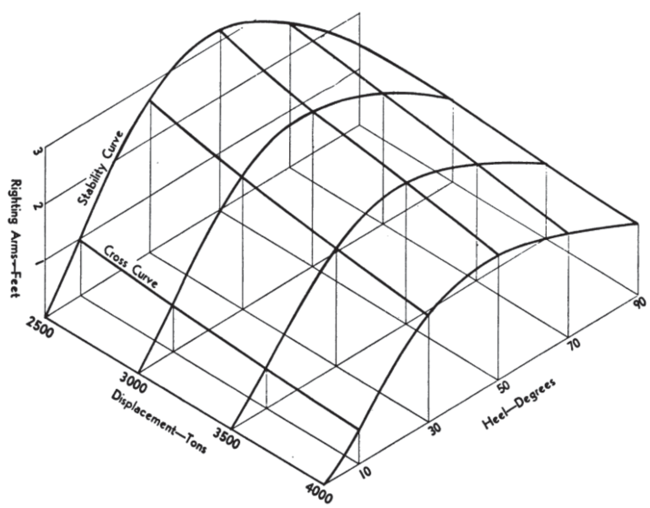


Fig. 16. GZ curve based on ship's displacement variation. [37]

- GZ maximum. This is crucial because both its value and the angle at which it occurs are proportional to the highest steady heeling moment the ship can withstand without capsizing.
- Stability range. The GZ value decreases to zero and turns negative for bigger inclinations at a certain angle, frequently greater than 90 degrees. The range of angles for which GZ is positive is referred to as the range of stability, and this angle is known as the angle of vanishing stability. When the heeling moment is released, a ship will return to the upright position at angles lower than this.
- Deck edge immersion angle There is a point of inflexion in the curve that, for the majority of ship forms, closely corresponds to the angle at which the deck edge submerges. However, for the bigger parts amidships, which have the greatest impact on stability, the angle at which the deck edge is immersed is often within a fairly small band. This point's significance lies less in its own right than in the fact that it instructs the designer on the potential impact of various design alterations on stability.
- Region beneath the curve. The area under the curve is a representation of the ship's capacity to absorb energy from winds, waves, or any other external force.

There are a few maritime organization responsible in safety and stability of ship such as International Maritime Organization (IMO) where they initiate The International Convention for the Safety of Life at Sea (SOLAS) to establishes minimal safety requirements for merchant ship design, building, and operation [54]. As ship comes variety of types, sizes, operational profile and environmental circumstances, IMO also implement International Code of Intact Stability, 2008) which outlines stability requirements that are both required and recommended, as well as other safety precautions, in order to ensure that ships operate safely and to reduce the risk to the environment, the people on board, and the ships themselves. A good and intact stability of ship means a stable equilibrium is achieved. In general, ship can be divided into three types of stability which are stable, neutral equilibrium. Fig. 17 below is the summary of those three conditions.

Those three stabilities from can be observed with the metacentric height (GM) condition.

- $GM > 0$ means the ship is stable.
- $GM = 0$ means the ship is neutrally stable.
- $GM < 0$ means the ship is unstable.

More configuration of stability and safety aspect with respect to regulation and legislation when added up the multi-stabilizer system into the vessel. For instances, gyrostabilizer which is an electrically powered-high rotation mechanism might be dangerous to crew if the system goes wrong. In such case, Takeuchi, Maeda and Umemura [40] highlighted that Mitsubishi anti-rolling gyrostabilizer is equipped with safety feature such as the ability to switch off the power supply if it is being used in high-wave circumstances. In term of legislation, Mitsubishi must adhere to the European registration, evaluation, authorization, and restriction of chemicals (REACH) regulations. In addition to this, even for tradition and non-automatic mechanism such as bilge keel need to be installed meticulously. This has been advised that according to The Australian Maritime Safety Authority (AMSA), problems can arise from the improper installation of fixed fin stabilizers [55]. The issues can be seen in Table 3 below.

IV. CONCLUSION

A diversity and unique stabilizers mechanism for marine vessel in providing stability inspire researchers, scientists and engineers to design, evolve and improve the existing devices for boosting the performance of roll stabilization. This review article presents a wide overview of design of

TABLE III
ISSUES AND RISKS ASSOCIATED WITH THE USE OF THESE PASSIVE/FIXED FIN STABILIZERS

Issues	Risks					
	Hull/ Vessel Damage	Sudden Heel	Lost Control	Capsize	Injury of Crew on-board	Damage/ Danger to Equipment
No formal design approval and no assessment by accredited marine surveyor of the structural integrity under pressure.	✓	✓	✓	✓	✓	-
Failure to lift stabilizers when crossing a bar or operating in shallow water.	✓	-	✓	✓	-	✓
Entanglement of stabilizers in fishing equipment.	✓	-	-	-	-	✓
Forgetting fins are out when berthing.	✓	-	-	-	-	✓
Installing and retrieving fins inadvertently.	=	-	-	-	✓	-

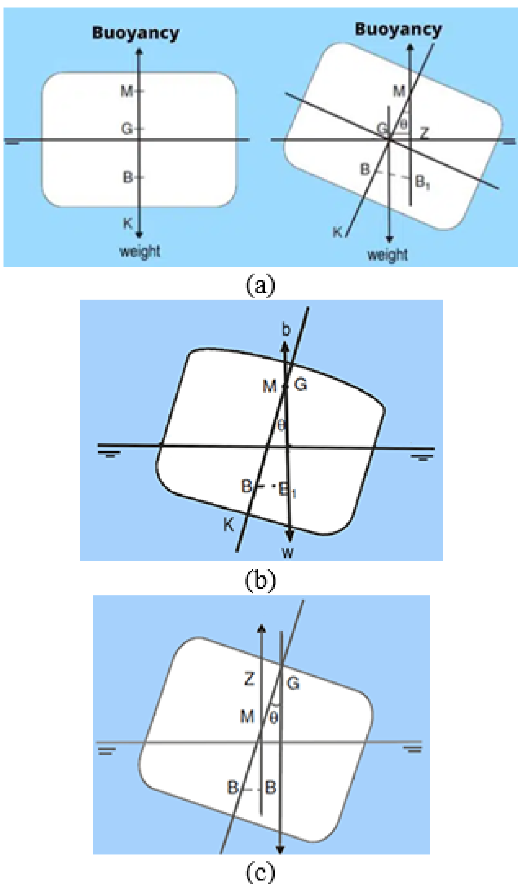


Fig. 17. Types of equilibrium of floating body. (a) Stable. (b) Neutral. (c) Unstable.

anti-rolling mechanism including their control in passive and active perspective done in the literature. An active system is very compelling in a way that it improves the operation and diminishes the burden of manpower. Advance technology of internal system has becoming more attractive and promising for their significant advantage by removing the drag and fluid resistance. Nevertheless, the it is external mechanism still in widely used for most of the vessel despite the types for its minimal in complexity and potential of reassuring in any situation in case of sudden dysfunctional of internal system. Hence, a future development and study on the amalgamation of both internal and external anti-rolling mechanism shall be explicitly done more for redundancy element as these are the potential research area for researches to look into with advancement in today's design, control strategies, dynamic and hydrodynamic modeling with the goal of achieving high performance and optimized power and size consumption on the vessel for a better efficiency in operation. It has been always a desire necessity to have roll reduction mechanism for marine related organization and seafarer could appreciate the benefits of preventing the occurring of damageable cargo, enabling comfort for crew and passengers and empowering crew to work efficiently.

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