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RESEARCH ARTICLE

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MECHANICAL GYROSCOPE-BASED ROLL MOTION REDUCTION OF MARINE VEHICLES: AN EDUCATIONAL SETUP*

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ABSTRACT

In this study, simple hardware (model boat and mechanical gyroscope) setup is presented to teach the fundamentals of angular momentum and gyroscopic stabilizing concepts. The tool consists of a model boat, hobby-type servo motor for generating roll motion, dc motor-powered mechanical gyroscope, a mini water pool, measuring, and control subsystems. A graphical user interface (GUI) with MATLAB was designed for adjusting and controlling the tool, observing and recording the roll motion of the model boat. Hence, the construction of the stabilizing torque is visually explained and presented within the setup as a product of angular momentum (due to spin of the flywheel) and external torque (due to external mechanical disturbance or waves). The tools help undergraduate students to understand what the gyroscopic effect is and how gyroscopic stabilizers dampen the roll motion of the model boat practically.

Keywords: *Gyrostabilizer, Roll Stabilization, Experimental Setup.*

MEKANİK JİROSKOP İLE DENİZ ARAÇLARINDA YALPA HAREKETİNİN SÖNÜMLENDİRİLMESİ: BİR EĞİTİM SETİ TASARIMI

ÖZ

Bu çalışmada, açısal momentum ve jiroskopik dengeleme kavramlarının öğretilmesi için tasarlanan basit bir deney düzeneği (model bot ve mekanik jiroskop) sunulmuştur. Deney düzeneği, model bir tekne, dalga benzetimi için bir servo sistemi, dc motor ile çalışan mekanik bir jiroskop, küçük bir su havuzu ile ölçme ve kontrol sisteminden oluşmaktadır. Deney setinin kontrolü, izlenmesi ve yalpa hareketinin kaydedilmesi için MATLAB tabanlı bir grafik ara yüzü tasarımı yapılmıştır. Bu sayede, açısal momentum (jiroskobun dönmesi) ve harici tork (dalga etkisi) ile oluşan dengeleme torku görsel olarak anlatılmıştır. Deney seti, lisans öğrencilerinin jiroskopik etkinin ne olduğunu ve jiroskopik dengeleyicilerin model teknenin yalpa hareketini pratik bir şekilde nasıl sönümlediğini anlamalarına yardımcı olur.

Anahtar Kelimeler: *Jiroskopik Dengeleyiciler, Yalpa Sönümleme, Deney Düzeneği.*

1. INTRODUCTION

Wave-induced roll motion is a major problem for marine vessels. This undesirable oscillating movement can reduce crew performance and passenger comfort, or can damage the cargo (Perez & Blanke, 2012). It is necessary to reduce the roll motion for safety and comfort. Various stabilizing systems are used in marine vehicles such as fin roll, rudder roll, magnus effect, moving mass, active tank, and gyroscopic stabilizers (Townsend & Shenoi, 2014). Rudder roll, fin roll, and magnus stabilizers are external systems that create the stabilizing torques outside the hull of the marine vessel. Active tanks, moving mass, and gyroscopic stabilizers are internal systems that create the stabilizing torques throughout the body (Towsend et al., 2007). Three types of ship stabilizer systems that are commonly used are the active fin stabilizers, the magnus effect stabilizers, and the gyroscopic stabilizers.

Two fins are placed on the port and starboard side of the ship in the active fin stabilizers. A gyroscopic sensor measures the roll angle of the ship and the fin controller adjusts the angle of the fins to reduce the roll motion. Magnus effect stabilizers use rotating cylinders instead of active fins as shown in Figure 1. The direction and speed of the cylinders are controlled with an electronic gyroscopic sensor and controller. Rotating cylinders use the magnus effect principle and generate up or down pressure according to their direction and rotation. Active fin and Magnus Effect stabilizer systems are closed-loop systems and designing a controller is necessary.

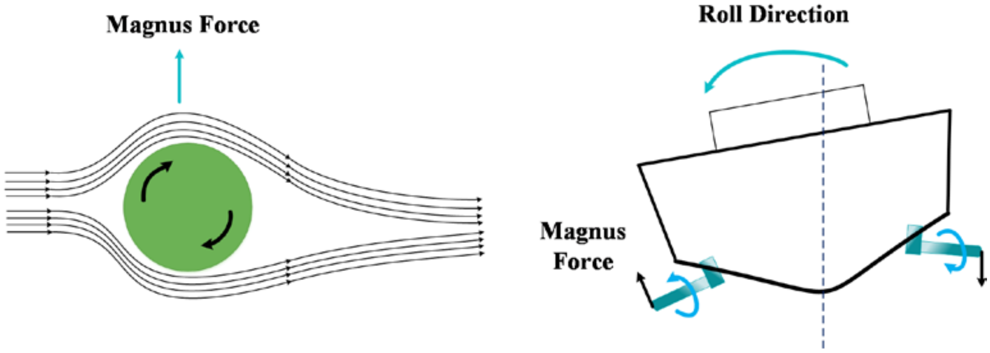

Figure 1. Magnus effect and rotor stabilizer.

Gyro stabilizers can be mounted to the inside of the ship. They use gyroscopic moments to reduce the roll motion of the ship. Gyro stabilizing is a passive and open-loop method, and it does not require a controller and a device for measuring roll motion.

The earliest suggestion of using gyroscopic stabilizers was made by Schlick (1904). Brennan (1903) and Forbes (1904) also proposed gyroscopic stabilizers for marine vessels. One of the first applications of gyroscopic stabilizers was made by Sperry (1910). Gyroscopic stabilizers have also been used in nonmarine applications such as two-wheeled vehicles (Karnopp, 2002), satellite systems, and autonomous underwater vehicles (Woolsey & Leonard, 2002). Yamada et al. (1997) used gyrostabilizers to control the wind-induced oscillations of tall buildings and high towers

Oleg et al. (2016) designed a robotic boat setup for control research and educational purposes. They aimed to develop the practical experience of the students with this setup. Lavieri et al. (2012) used an experimental boat set up to develop a sliding mode controller for reducing the roll motion. Gyro stable platform (Quanser, n.d.) and Control Moment Gyroscope (ECP, n.d.) are commercial training sets designed for educational purposes. These training sets are used to investigate the rotational dynamics of gyroscopes. In principle, these educational sets are related to the concept of reorientation of space satellite problems. Several satellites now provide commercial earth imagery for customers (such as Google Earth etc.). The earth imagery requires an agile satellite, meaning that the satellite achieves comparatively high angular rates and accelerations to reorient itself and slew payloads quickly from one attitude to another. A technology known as the control moment gyroscope makes satellites sufficiently agile (Leve et al., 2015). Up to 3 axes can be controlled and reoriented this way. One other example of the gyroscopic effect is missile stability. Most likely, in close range, the most widely used air to air missile is the Sidewinder in the West, with roughly over 100,000 missiles produced for more than two dozen nations. It has four fins at the back of the missile that provides stability and four movable control surfaces are located in the front part, just behind the infrared seeker. This configuration has a natural tendency of roll motion that makes guidance and control difficult. To prevent roll motion (spinning around its longitudinal axes) and to simplify the aerodynamic structure, a clever solution has been proposed and used. Four metal discs (rollerons or a kind of rotor) are attached at the end of the four tail wings. Once the missile is fired, due to high speed, all four rollerons spin at very high rpm and prevent any undesired roll motion. This gyroscopic effect in the tail wing prevents the missile from spinning in flight (Taur & Chern, 1999). It is effective and is still in use. Recently, in a similar principle of stabilizing effect of the fast-spinning rotor, several companies have produced marine stabilizers commercially. Commercial products of well-known companies are shown in Figure 2 (Seakeeper, n.d.) (DMS, n.d.), (Wesmar, n.d.).

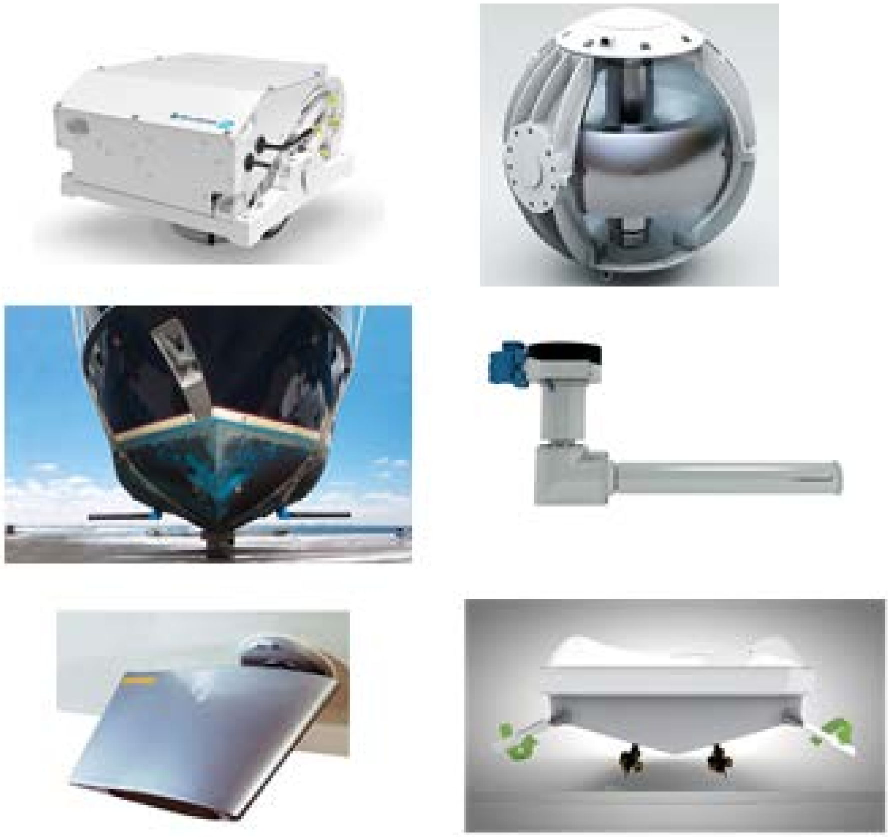

Figure 2. Various boat stabilizers: Gyrostabilizer, rotor stabilizers, fin roll stabilizers (Seakeeper, n.d.), (DMS, n.d.), (Wesmar, n.d.).

This paper presents a demo setup for understanding the concept of the gyroscopic effects for the wide sense gyroscopic stabilizing process, which was not explicitly discussed in Electrical Engineering majors at OMÜ, Samsun, Türkiye. The tool was designed for the undergraduate level Automatic Control Laboratory and Autonomous Vehicle Applications courses given for the same department. As it is known, applied teaching plays a key role in engineering education (Bernstein, 1999) and this setup serves this purpose.

The rest of the paper is organized as follows. Section 2 gives the working principle of gyroscopic stabilizers. Section 3 provides the details of the educational tool design. Experimental results obtained from the setup are provided in Section 4. Finally, conclusions obtained from the practical construction of the setup and experimentation are provided in Section 5.

2. PRINCIPLE OF GYROSCOPIC STABILIZERS

A rotating flywheel produces an angular momentum that is perpendicular to the plane of rotation. Angular momentum is a vector quantity and its direction can be determined by the right-hand rule as seen in Figure 3.

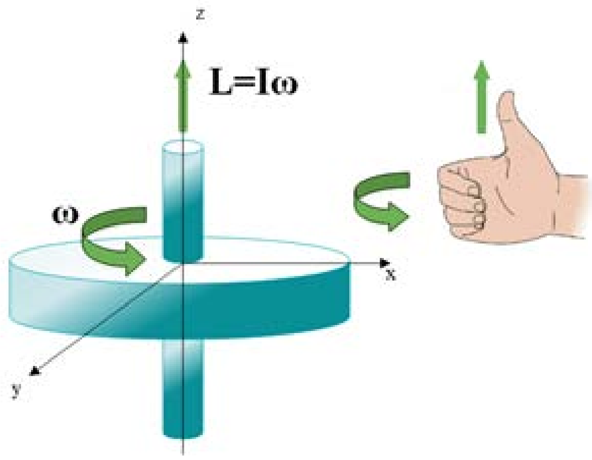

Figure 3. Angular momentum of rotating flywheel.

Angular momentum is the product of moment of inertia, I and Angular Velocity, ω

$$\vec{L} = I\vec{\omega} \quad \textbf{(1)}$$

To investigate the principles of gyroscopic stabilizers we can consider a gyroscope that is symmetrical about the z-axis and free to rotate about its three axes as shown in Figure 4. The gyroscope has a spin rate, φ, and angular momentum, L. Acting moments of each axis (M_x, M_y and M_z) can be derived from general equations of motion (Housner & Hudson, 1959). ω_x, ω_y, and ω_z are the angular velocities for each axis and $\dot{\varphi}$ is the spin rate of the gyroscope.

$$M_x = I(\dot{\omega}_x - \omega_y\omega_z) + I_z\omega_y(\omega_z + \dot{\varphi}) \quad \textbf{(2)}$$
$$M_y = I(\dot{\omega}_y - \omega_x\omega_z) - I_z\omega_x(\omega_z + \dot{\varphi}) \quad \textbf{(3)}$$
$$M_z = I_z(\dot{\omega}_z + \dot{\varphi}) \quad \textbf{(4)}$$

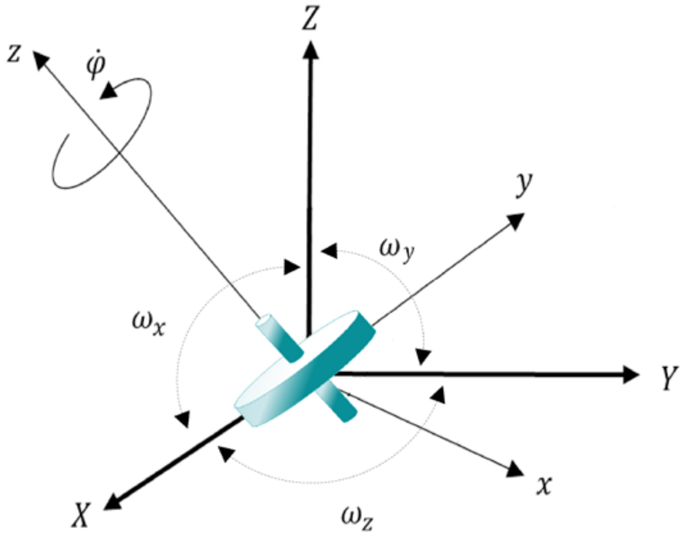

Figure 4. Axes of a gyroscope.

If we examine (2), (3), and (4) we can see the additional moments that are related to the spin rate of the flywheel ($\dot{\varphi}$).

$$M_x = I_z \omega_y \dot{\varphi} \quad \textbf{(5)}$$
$$M_y = -I_z \omega_x \dot{\varphi} \quad \textbf{(6)}$$

M_x and M_y are called gyroscopic moments. According to (5) and (6), the gyroscopic moment acting on the x-axis is related to the angular velocity of the y-axis, and the moment acting on the y-axis is related to the angular velocity of the x-axis. Therefore, if a force is applied to any axis of the gyroscope, it produces a moment perpendicular to the applied force.
When the gyroscope is used as a marine stabilizer, one of its axes is fixed to the ship's rolling axis. The gyroscope is free to rotate about the pitch axis. Stabilizing torque is created in three steps and these steps occur at the same time.
1) Sea waves make the boat roll. This can be represented with a force (F_x) pair along the x-axis. At that time the gyroscope is rotating counterclockwise direction and produces an angular momentum on the z-axis.
2) The gyroscope rolls with the boat because it is fixed to the roll axis. The gyroscope has an ω_x angular velocity because of the roll motion. According to (6) this angular velocity produces a moment (M_y) in the y-axis as seen in Figure 5. M_y results as a direction change (ΔL) in angular momentum (Lewin, 2015) and gyroscope sweeps along the y-axis. This motion is called the precession of the gyroscope. L_1 is the resultant angular momentum.

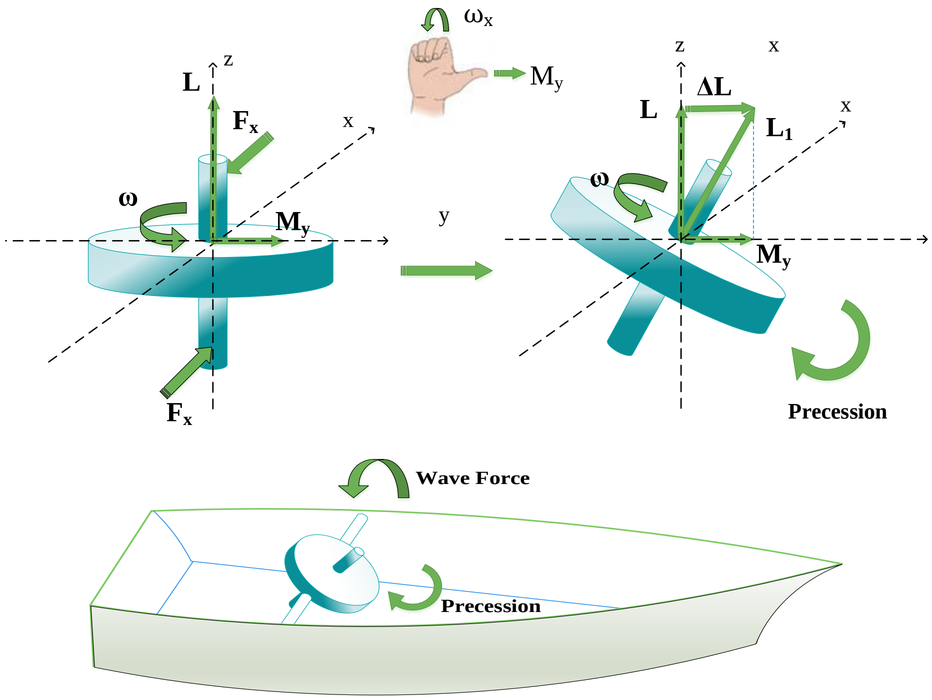

Figure 5. Change of angular momentum of the gyroscope.

3) Gyroscope has an angular ω_y velocity because of the precession motion. This angular velocity produces a momentum (M_x) perpendicular to its direction according to (5) as seen in Figure 6. Angular velocity (ω_y) has the maximum value at the beginning of the precession motion and consequently M_x is maximum at that time. M_x and L_1 result as M_s stabilizing moment. This moment is in the same plane but opposite direction of the roll motion and is called stabilizing moment. The stabilizing moment occurs at the same time as the precession motion and resists the forces caused by the sea waves.

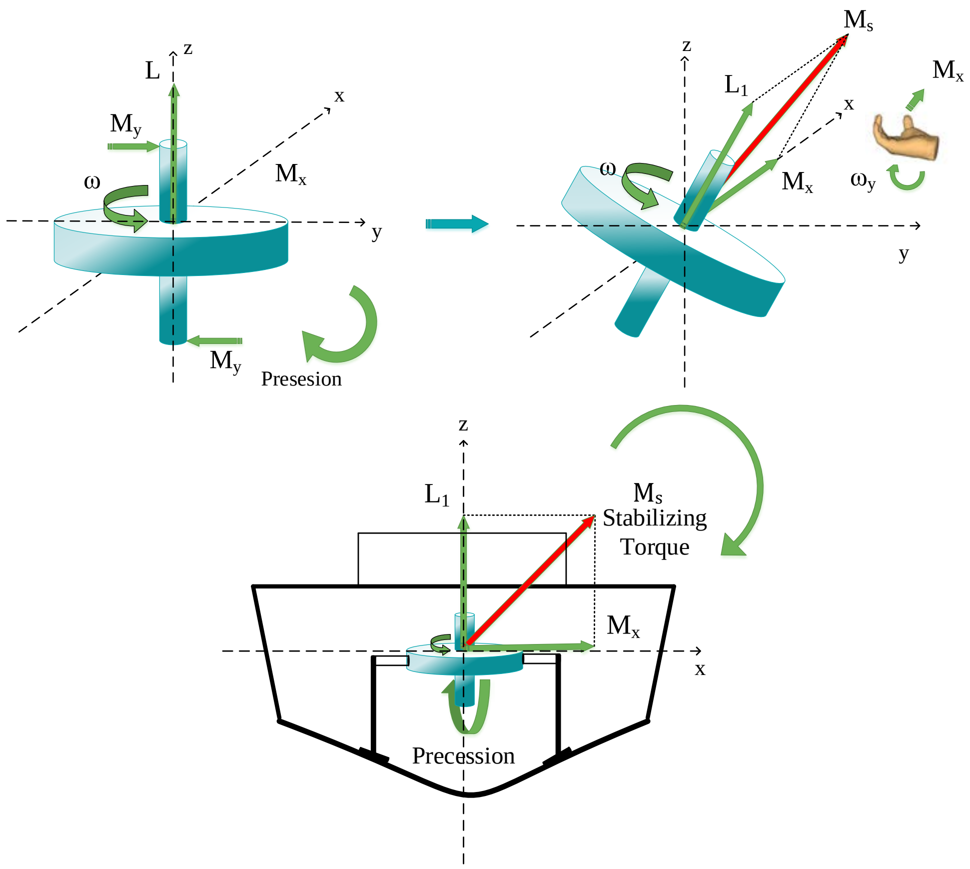

Figure 6. Creation of stabilizing moment.

3. DESIGN OF THE EDUCATIONAL TOOL

Two experimental setups were designed: dry and wet. The dry setup is designed for use in the laboratory without the need for water and the wet setup is for use with water. The dry setup consists of a mechanical gyroscope, a model boat, a servo system for roll motion generation, and a control circuit to measure the angle of roll motion and drive the servo motor with the intended speed. The model boat that weighs 3 kg is placed on a wooden base and can freely move on the roll axis. A servo motor is attached to the body of the boat with a stretchy rope. The stretchy rope stimulates the boat in the forward and backward directions as well as allows the gyroscope to get over the wave forces that are generated by the servo system. The servo system swings the boat on the roll axis. These pull and release motions simulate the boat roll due to water waves. The speed of the servo motor can be adjusted to change the stimulated wave effect (amplitude and frequency). The general view of the dry setup is shown in Figure 7.

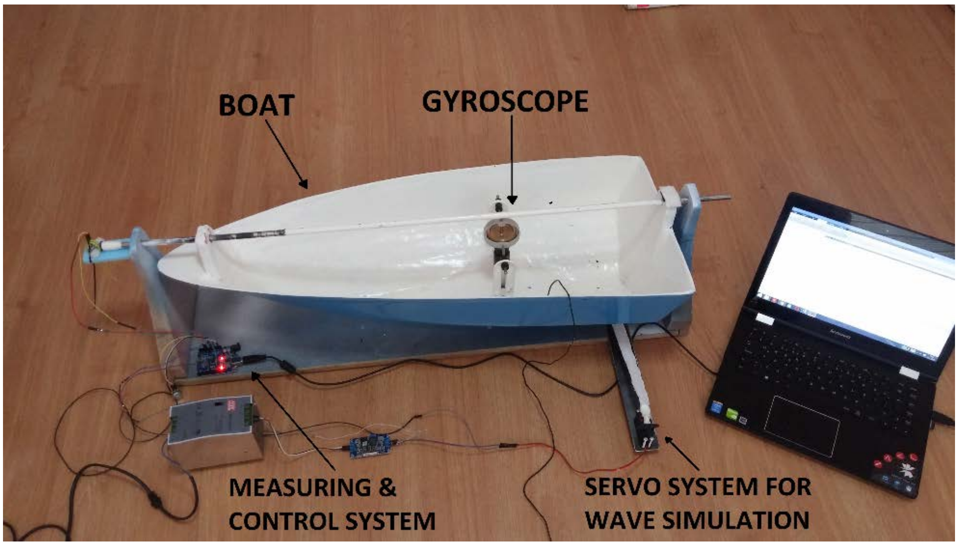

Figure 7. General view of the dry setup.

The general view of the wet setup is shown in Figure 8. It consists of a model boat, a mini water pool, a servo motor for roll motion generation, a mechanical gyroscope, and an electronic control system. The model boat weighs 1 kg and it can freely move on the water. A geared dc motor and a metal plate are assembled to generate waves. The metal plate is moved forward and backward periodically in the water to generate waves. The amplitude and frequency of waves can be adjusted by motor speed and angle of the metal plate.

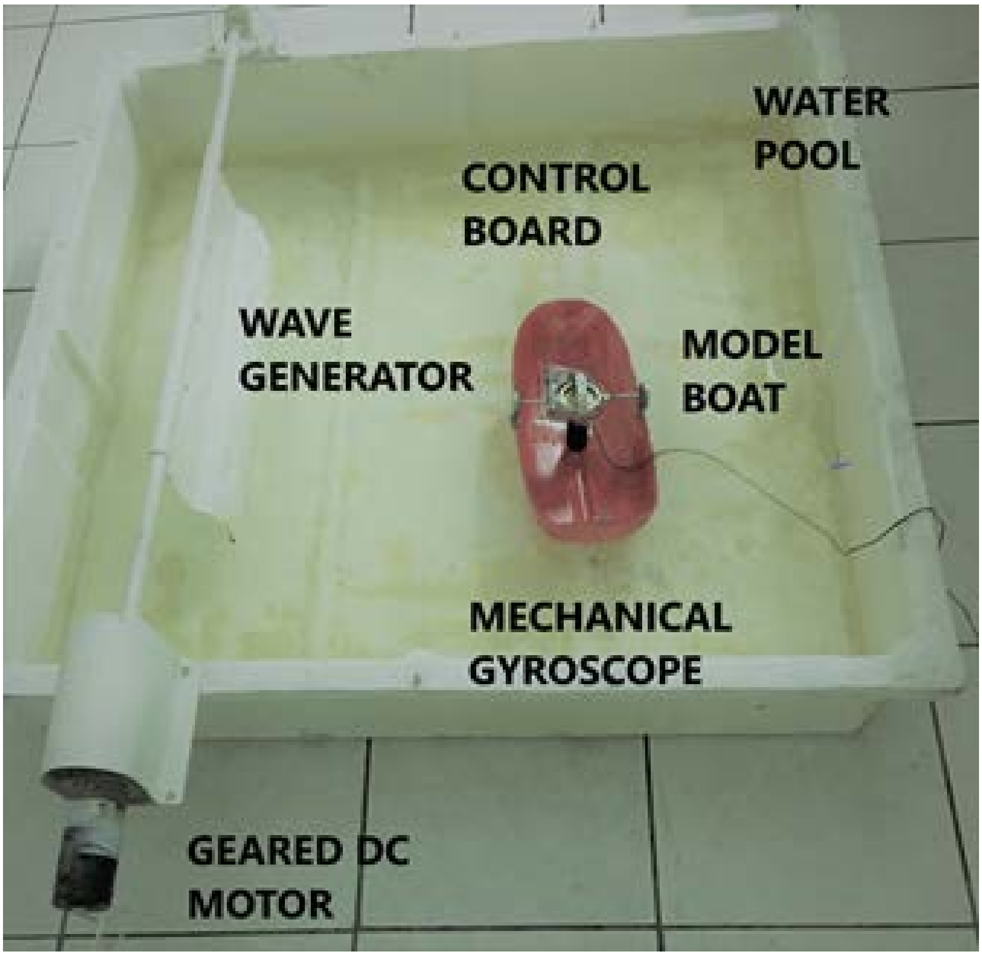

Figure 8. General view of the wet setup.

A mechanical gyroscope that is made of brass material is used as a stabilizer. The used gyroscope can be seen on the website at (Gyroscope, n.d.). It has an aluminum frame for bushing and fixing. It is driven by a dc motor that runs up to 12000 rpm. The total weight of the gyroscope is 145 g without the motor and its outer diameter is 62.5 mm. The mechanical gyroscope with dc motor is shown in Figure 9.

Figure 9. Mechanical gyroscope.

Three-axis gyro and accelerometer sensor MPU6050 is used to measure the angle of roll motion. It is widely used in acceleration and angle measurements because of its accuracy and low cost. The general diagram of the system is shown in Figure 10.

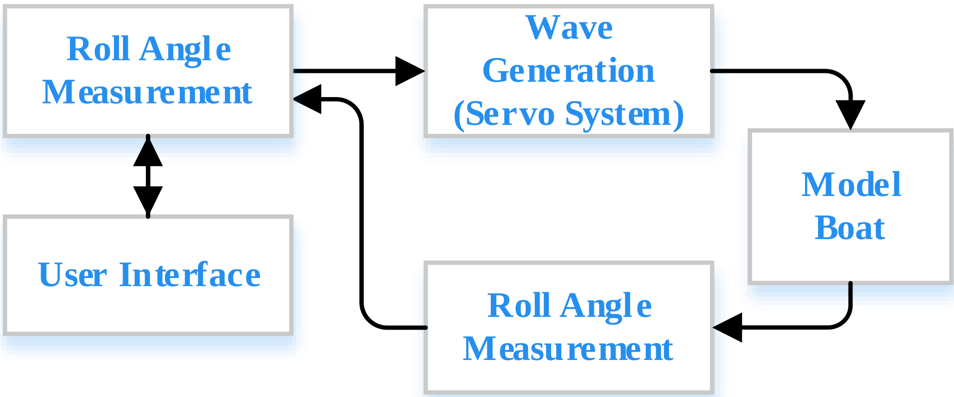

Figure 10. General block diagram of the system.

A MATLAB-based graphical user panel is designed to monitor and control the experimental setup. Control of the gyroscope and servo system can be set via the user panel. The angle of the boat's roll motion can be monitored and recorded with the panel. The user panel can be seen in Figure 11.

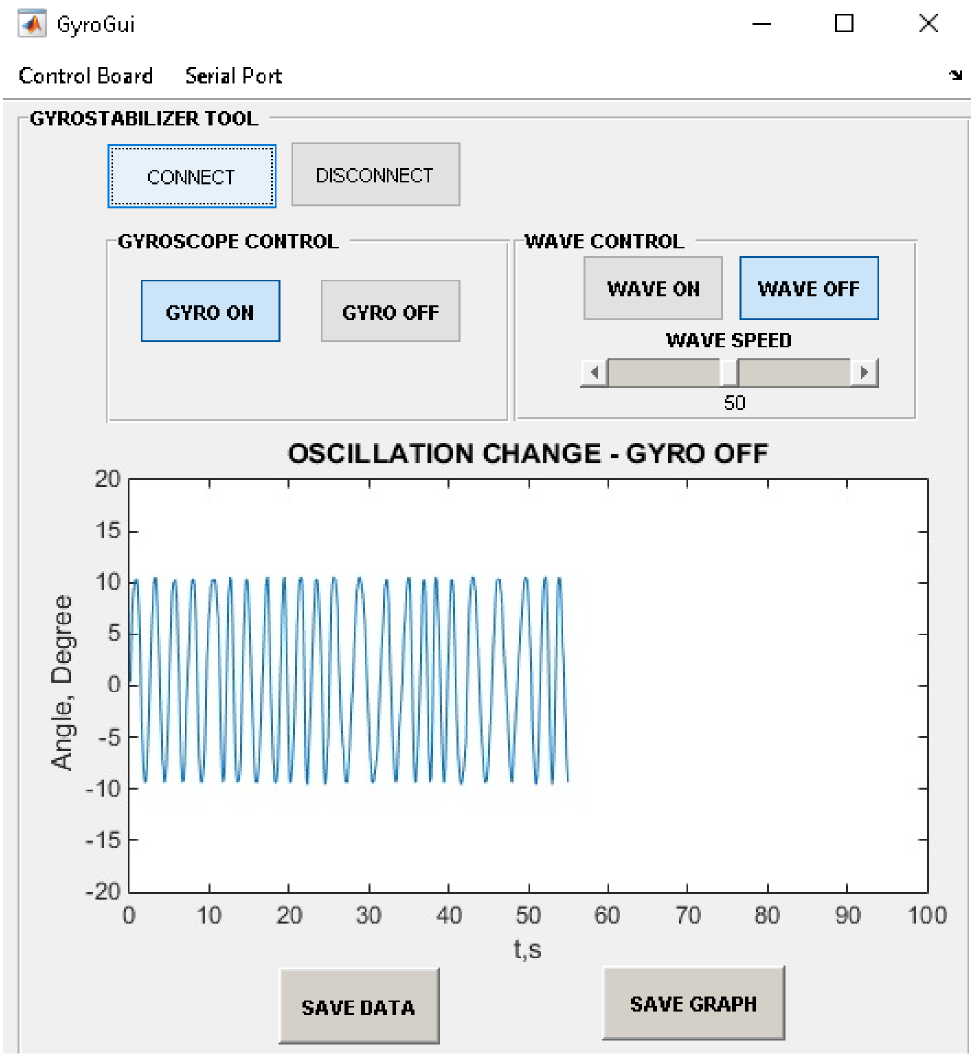

Figure 11. Graphical user interface panel.

4. EXPERIMENTAL RESULTS

The roll angle of the model boat was measured right after releasing the boat from a roll angle position of 20 Degree. The change in the natural rolling motion is shown in Figure 12. This data can be useful for modeling and finding the damping characteristics of the system (Ertogan et al., 2018).

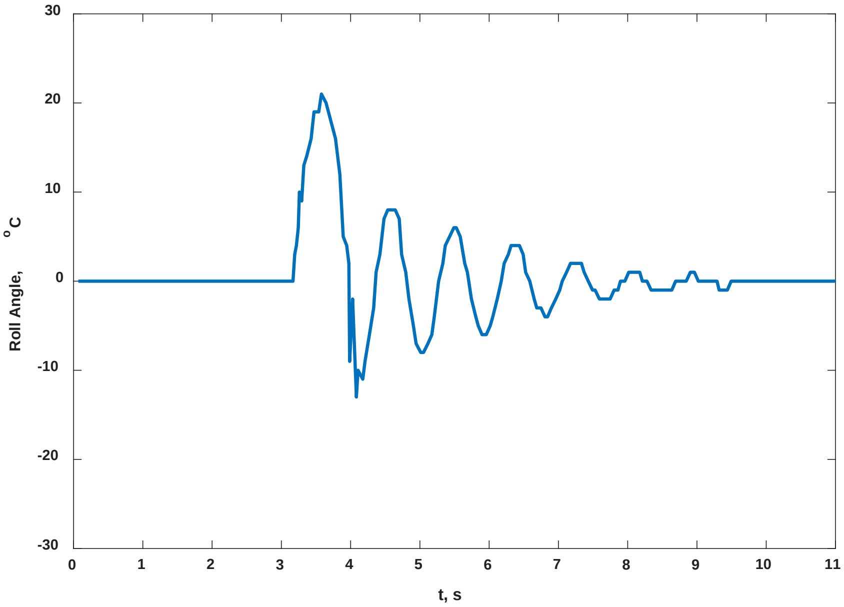

Figure 12. Natural roll motion of the model boat.

The gyroscopic effect and creation of the stabilizing moment can be explained step by step with the dry setup. Before running the setup automatically, the vectorial quantity of angular momentum and external torque acting on the boat and the precession of the gyroscope were investigated. When the gyroscope runs at full speed and rotates clockwise direction the angular momentum occurs towards the bottom of the boat. The direction of the angular momentum is shown in Figure 13.

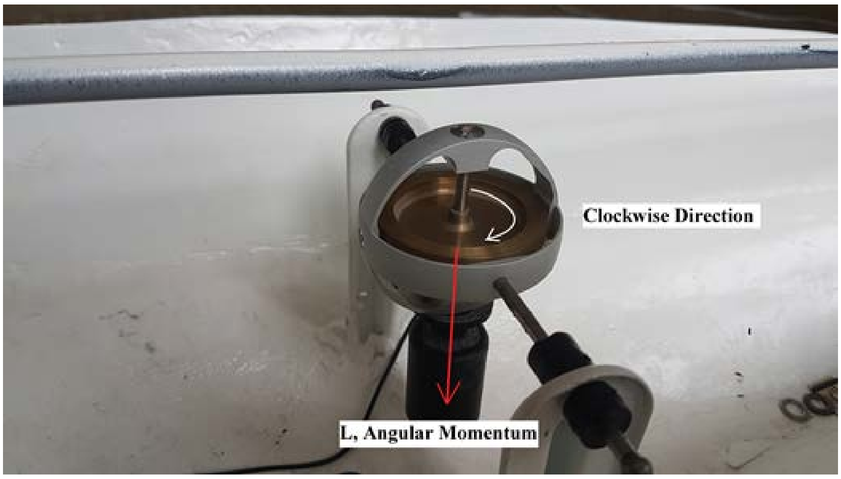

Figure 13. Angular momentum of a mechanical gyroscope.

Manual forces applied to the boat can explain the precession of the gyroscope. A force was manually applied to the starboard of the boat by hand while the mechanical gyroscope was rotating clockwise direction. According to the right-hand rule precession motion of the gyroscope is to the foreship direction (or bow part) as seen in Figure 14. It can be confidently stated that Angular momentum (L) always follows external torque (M_y) and L1 (stabilizing torque) comes into existence by product of L and M_y.

Figure 14. Precession motion of the gyroscope while a force is applied to the starboard of the boat.

When the force is applied to the port side of the boat by hand while the mechanical gyroscope is rotating clockwise, the precession motion of the gyroscope is towards the aft part of the boat (or stern part) as seen in Figure 15.

Figure 15. Precession motion of the gyroscope while a force is applied to the larboard of the boat.

A pair of forces (F) that mimics hand force applied to the port side of the boat is in the y plane as seen in Figure 16. The gyroscope has an angular velocity ω_y because of the precession. This angular velocity and gyroscope spin rate result in a moment in the x-axis, according to equation (5). This M_s torque (moment) is in the opposite direction of the applied force and is called stabilizing torque.

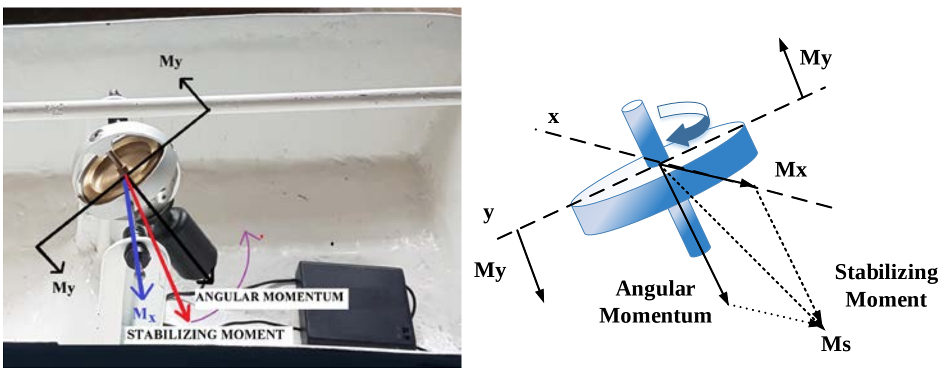

Figure 16. Creation of the stabilizing moment.

The boat of dry setup was made to roll at an average wave speed with the servo system. Figure 17 shows the roll angle while the gyroscope is on and off. The roll angle was ±10 degrees while the gyroscope was not operating. Two minutes after the gyroscope was powered on, the roll angle was measured as ±2 degrees. The transition of the roll angle, while the gyroscope is initially powered on and later on powered off, is shown in Figure 18.

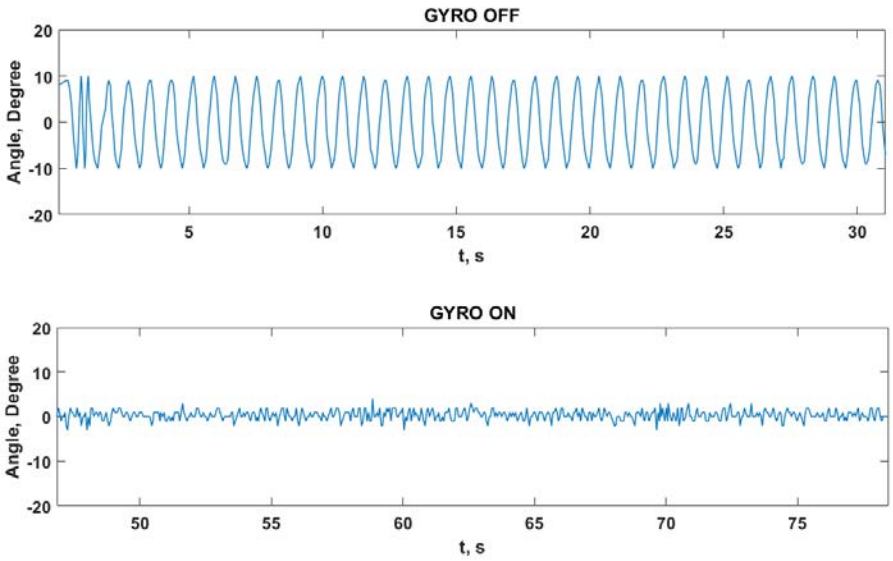

Figure 17. The angle of roll motion of the model boat when the gyroscope is on and off for the dry setup.

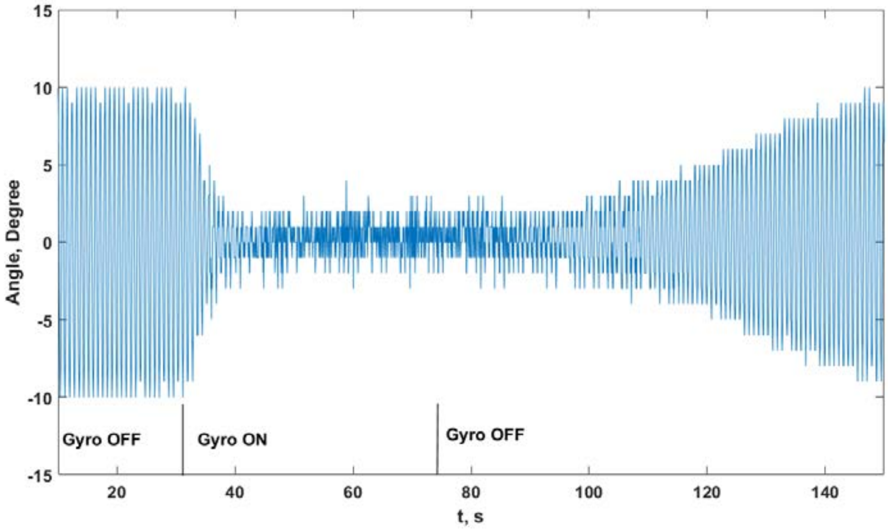

Figure 18. The angle of roll motion of the model boat while on and off transitions of the gyroscope for the dry setup.

The second experiment was conducted in the mini water pool with the wet setup. The wave generator was run, and the roll angle was measured and recorded. The roll angle change is shown in Figure 19 and Figure 20 while the gyroscope is powered on and off, respectively. While the gyroscope is off, the angle of the roll motion is approximately ±30 degrees. After the gyroscope is turned on, the angle decreases to a range of ±6 to ±8 degrees.

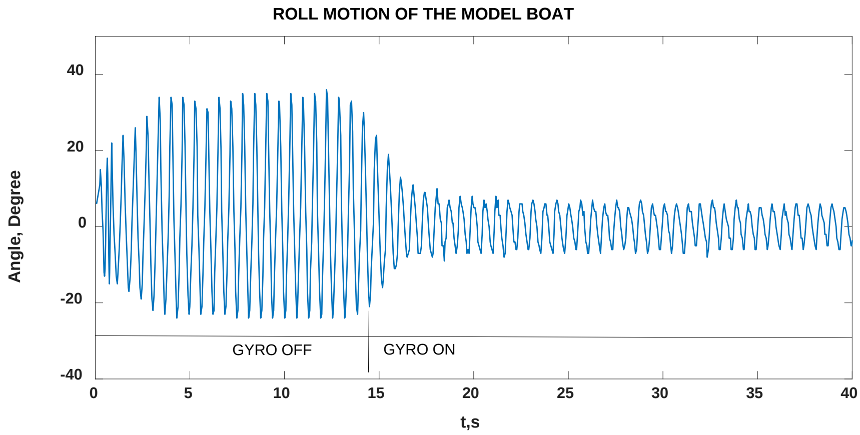

Figure 19. The angle of roll motion of the model boat when the gyroscope is on and off for the wet setup.

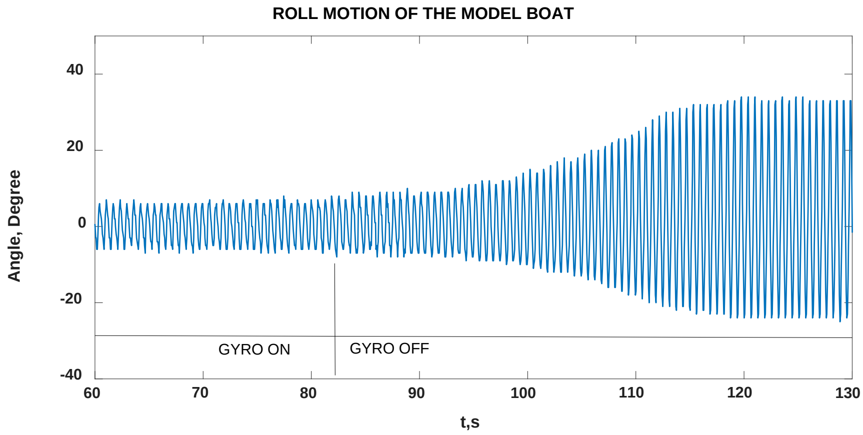

Figure 20. The angle of roll motion of the model boat when the gyroscope is on and off for the wet setup.

5. CONCLUSION

Design of educational setups of gyro stabilizers for model marine boats is presented. Electrical and mechanical parts (model boat, dc powered gyroscope, wave generation, measurement of the angle of roll via GUI) of the setups were explained in detail. The performance of the gyro stabilizers was investigated in dry and wet setups and the results were presented. Damping of roll motion of model boats is presented experimentally and the obtained results are discussed. The mechanism of counterforce to balance the wave-generated roll motion is explained and discussed in terms of momentums given in (5) and (6), which include the spin rate and precession motion of the flywheel. The construction of stabilizing torque is alternatively explained and visually depicted with the combination (product) of two vectors (angular momentum vector -due to spin of the flywheel- and external torque –resulting from roll motion of the model due to waves-) in pictures. The second explanation (or combination of two vectors) is easy to trace for students.

Generally speaking, the developed tools will be useful for mechanic, physic, and control laboratories at undergraduate and graduate levels. They will also assist students and researchers in their research on angular momentum and gyroscopic effects.

The current setup provides a basic understanding of the stabilization of the marine vehicle systems and highlights the practical issues in the construction of such a system. Future extensions of the study are to add fin stabilizers and rotor stabilizers to the existing setup to investigate and compare the stabilizing methods. Another future work is to construct a larger wet setup to simulate more realistic ocean waves is being considered, which will be used to develop a control system applying artificial intelligence for marine vehicle stabilization.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

REFERENCES

Bernstein, D. S. (1999). "Enhancing undergraduate control education". *IEEE Control System Magazin*, 19(5), 40-43.

Brennan, L. (1903). *Improvements in and relating to the imparting of stability to otherwise unstable bodies, structures or vehicles* (UK Patent No. 27,212).

DMS (n.d.). "DMS Magnus Master". Retrieved from https://www.dmsholland.com/en/stabilizers/magnusmaster-2/

ECP (n.d.). "Model 750: Control Moment Gyroscope". Retrieved from http://www.ecpsystems.com/controls_ctrlgyro.htm

Ertogan, M., Ertuğrul, S., Wilson, P. A., & Tayyar, G. T. (2018). "Marine measurement and real-time control systems with case studies". *Ocean Engineering*, 159(1), 457-469.

Forbes, T. C. (1904). *Device for steadying ships* (USA Patent No. 769693).

Gyroscope (n.d.). "Super Precision Gyroscope (without gimbals)". Retrieved from https://www.gyroscope.com/d.asp?product=SUPER2

Housner, G. W., & Hudson, D. E. (1959). *Applied Mechanics Dynamic.* Van Nostrand Company, Inc.

Karnopp, D. (2002). "Tilt control for gyro-stabilized two-wheeled vehicles". *Vehicle System Dynamics*, 37(2), 145-156.

Lavieri, R. S., Getschko, N., & Tannuri, E. A. (2012). "Roll Stabilization Control System by Sliding Mode". In *9th IFAC Conference on Manoeuvring and Control of Marine Craft*, 45(27), 448-452.

Leve, F. A., Hamilton, B. J., & Peck, M. A. (2015). *Spacecraft Momentum Control Systems.* Springer, Cham.

Lewin, W. (2015, February 08). *Lect 24 - Rolling Motion, Gyroscopes* [Video]. Youtube. Retrieved from https://www.youtube.com/watch?v=XPUuF_dECVI

Oleg, I. B., Vladislav, S. G., Anton, A. P., Alexey, A. B., & Nikolay, A. N. (2016). “Robotic Boat Setup for Control Research and Education”. *IFAC-PapersOnLine,* 49(6), 256-251.

Perez, T., & Blanke, M. (2012). “Ship roll damping control”. *Annual Reviews in Control*, 36(1), 129-147.

Quanser (n.d.). “Gyro/Stable Platform”. Retrieved from https://www.quanser.com/products/gyrostable-platform/

Schlick, E. O. (1904). “The gyroscopic effect of flywheels on board ship”. *Transactions of the Institute of Naval Architects*, 23(1), 117-134.

Seakeeper (n.d.). “Seakeeper Gyrostabilizers”. Retrieved from https://www.seakeeper.com/

Sperry, E. A. (1910). “The gyroscope for marine purposes”. *Transactions of the Society of Naval Architects and Marine Engineers*, 18(1), 143.

Taur, D. R., & Chern, J. S. (1999). “Rolleron dynamics in missile applications”. In *24th Atmospheric Flight Mechanics Conference*, 718-733.

Towsend, N. C., Murphy, A. J., & Shenoi, R. A. (2007). “A new active gyrostabilizer system for ride control of marine vehicles”. *Ocean Engineering*, 34(1), 1607-1617.

Townsend, N. C., & Shenoi, R. A. (2014). “Control Strategies for Marine Gyrostabilizers”. *IEEE Journal of Oceanic Engineering,* 39(2), 243-255.

Wesmar (n.d.). "Roll Fin Stabilizing Systems". Retrieved from https://www.wesmar.com/commercial-fin-stabilizer-systems

Woolsey, C. A., & Leonard, N. E. (2002). "Stabilizing underwater vehicle motion using internal rotors". *Automatica*, 38(12), 2053-2062.

Yamada, M., Higashiyama, H., Namiki, M., & Kazao, Y. (1997). "Active vibration control system using a gyro-stabilizer". *Control Engineering Practice*, 5(9), 1217-1222.