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THE APPLICATION OF OPTICAL GYROSCOPE IN DEVELOPING INERTIAL NAVIGATION SYSTEM

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ABSTRACT

The reduction in cost and size for navigational equipment plays a significant role in meeting the demands of the maritime industry in compliance with performance and reliability. The conventional mechanical gyroscope depends on its heavy and bulky configuration to achieve its commercial maturity. Hence, new technologies, such as optical fibre, are being developed as an alternative for the mechanical gyroscope. Optical fibre is a technology that offers a higher performance due to its exceptional accuracy even at a significantly smaller configuration. Instead of using the same principle as mechanical gyroscopes, optical gyroscopes apply the Sagnac Effect, which utilises light to measure the motion of the vehicle. The different configurations of optical gyroscopes allow them to be generally categorised into two, Fibre Optic Gyroscope and Ring Laser gyroscope. Optical gyroscopes are expected to have stable and consistent market analysis growth as they offer exceptional performance. Due to its reliability, optical gyroscopes are implemented in modern technologies. One of them is the Inertial Navigation System, a system that measures and tracks the position, movement, and orientation of the vessel. The attitude of the vessel can be measured in all three-dimensional axes, allowing six degrees of freedom of the vessel to be determined. To construct a reliable Inertial Navigation system, a triad of accurate gyroscopes are needed, and optical gyroscopes are the unrivalled choice to serve that purpose.

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Inertial Navigation System

1.0 INTRODUCTION

The marine gyrocompass is one of the earliest systems based on the gyroscopic principles, which are the rigidity in space (inertia) and precession. A rapid rotating top will align its angular momentum with the earth's rotating angular momentum, and it will indicate the heading towards the geographical North, resembling a standard magnetic compass aligning its magnetic properties with the Earth's terrestrial magnetic field (Frost, 1982).

The word 'gyroscope' originates from the Ancient Greek language, describing the precession motion. It is conventionally referred to as the typical mechanical type of gyroscope (Passaro et al., 2017). Generally, the gyroscope is a device that can sense a torque when a mounted frame is rotating, which later produces an angular velocity. There are different classes of gyroscopes categorised according to the technology involved and its physical properties (Passaro et al., 2017). In terms of construction and working principle, gyroscopes are generally identified as Coriolis gyroscope, levitated rotor gyroscope, Sagnac gyroscope and nuclear magnetic resonance (NMR) gyroscope (Kai Liu, 2009).

The marine gyrocompass has been utilised since the 1920s and is highly maintenance-intensive, and it also offers limited reliability in life usage. However, increasing demand for precise information on vessels' attitudes is made for survey vessels. The demands for positional reference of vessels are not focused on the information of true heading only but also covers the complete data of vessels' attitude (roll, pitch, heave, surge, sway, etc.). At the present time, these demands are fulfilled by complimenting a conventional gyrocompass with a motion sensor, but in underwater applications, the disadvantages of the conventional gyrocompass become apparent (Gaiffe et al., 2000). They are heavy and bulky, making them difficult to transport. They also consume much power, need several hours to boot and offer limited roll and pitch angles only (Gaiffe et al., 2000).

In recent years, military and civil aeronautical applications have dismissed the utilisation of mechanical and conventional gyroscopes while favouring more modern, "strapdown" technologies (Titterton, 2004). Since these technologies are constructed with little to no moving parts, their advantages over gimbals-mounted systems become even more marked as they are more robust and demand less maintenance. Mechanical gyroscopes are then substituted by optical gyroscope; Fibre Optic Gyroscope (FOG), or Ring Laser Gyroscope (RLG).

In the effort to improve the maritime industry, continuous and constant developments are compulsory for both inshore and offshore parties. In terms of the gyrocompass used in the industry, excluding the tuned-motor gyroscope, other types of gyroscopes can also be utilised, such as FOG and RLG. Although these two gyroscopes possess the identical function as the tuned-motor, which is to seek an azimuth (geographical North), they implement a different concept which is the Sagnac Effect (Juang & Radharamanan, 2009). A gyroscope is applicable and practical to be used by itself or when included in a more complex system such as Inertial Measurement Unit, Gyrocompass (Elliott-Laboratories et al., 2003) and Inertial Navigation System (King, 1998).

An Inertial Navigation System (INS) is a system that measures both angular and linear motion of a vehicle, with respect to its inertial space, the initial position when at rest or moving, in an effort to determine the vessel's orientation, velocity and position. Due to their reliability, INSs are used on mobile robots (Cook, 2011) and also on vehicles such as aircrafts, guided missiles, submarines, ships and space crafts (Hoag, 1963). Several examples of INS utilise the FOG technology in its configuration. One of them is Boreas, the world's first fully digital FOG that was developed by Advanced Navigation (Recouvreur, 2021), and another one is Octans by Photonetics (Gaiffe et al., 2000)

2.0 LITERATURE REVIEW

2.1 OPTICAL GYROSCOPE

Optical gyroscopes work by sensing the propagation's time difference between two counter-propagating beams that travel in a closed or open optical path. Any change in the path lengths induced by rotation will create a phase difference between the two beams, which is the basis of the Sagnac Effect, the operating principle of all-optical gyroscopes (Passaro et al., 2017). However, the technique used to measure the Sagnac Effect differs from each configuration, making it possible to categorise optical gyroscopes accordingly. There are mainly two types of optical gyroscopes, active and passive configuration (Passaro et al., 2017) (see figure 1).

The configuration for active sensor gyroscopes is built in two different constructions: Bulk Optics or Integrated Optics technology. However, only Bulk Optic's construction has achieved commercial maturity (Passaro et al., 2017). Ring Laser Gyroscopes are distinguished between classes according to the method utilised to counter the lock-in effect, the condition where an active sensor is insensitive to low rotation changes. The methods are by introducing a mechanical dither, a magneto-optic biasing, or multiple optic frequency configurations.

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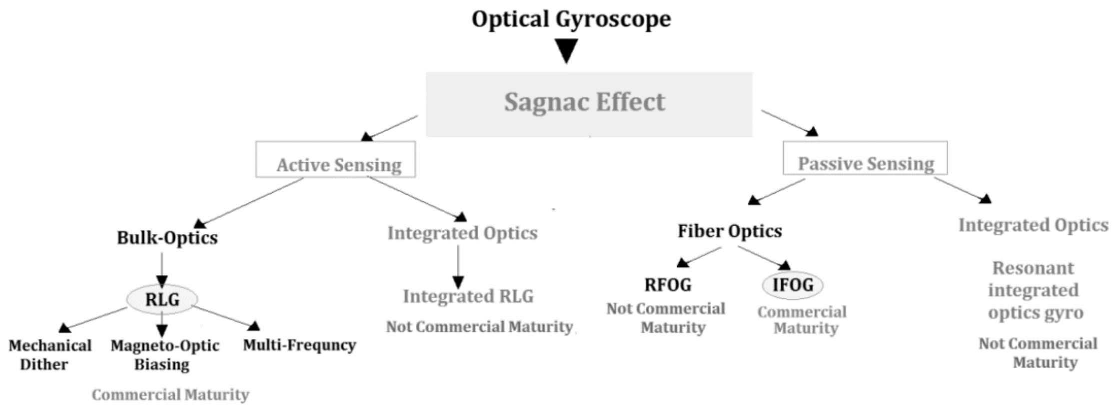

Figure 1: Types of Optical Gyroscopes (Passaro et al., 2017)

2.2 SAGNAC EFFECT

Sagnac Interference, often identified as Sagnac Effect, is a phenomenon observed in interferometry, a setup to manifest the effect, and is obtained by rotation of the interferometry (Arditty & Lefèvre, 1981). The effect takes place when a beam of light is split into two, and each of them will propagate in the direction opposite of one another but one identical path. Upon returning to the point of entry, both beams will then combine to undergo interference.

In a non-rotating frame, the phase of both beams of light is identical; however, when the frame is rotating, the phases of both beams are different according to the angular velocity of the rotating frame. This is due to the longer path that one of the beams propagates through compared to the other beam that took a shorter path (Arditty & Lefèvre, 1981).

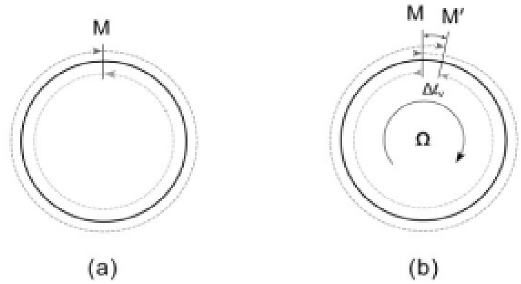

Figure 2: Sagnac Effect (Arditty & Lefèvre, 1981)

A mechanical gyroscope applies the principle of angular momentum's conservation which helps it remains to point in one fixed direction by keeping its spinning motion. Comparatively, RLG and FOG are based on the Sagnac Effect, which relies on the constant speed of light for all inertial frames of reference. Hence, bulky mechanical gyroscopes are replaceable by those with no moving parts. This will assist the development of the modern inertial navigational system. The configuration used in measuring the Sagnac Effect in RLG and FOG differ from each other, and the differences act as the distinctions between the two by determining their weight, size, power requirements, cost, and performance (Juang & Radharamanan, 2009).

2.3 RING LASER GYROSCOPE (RLG)

Ring Laser Gyroscope (RLG) utilised two independent counter-propagating ring lasers inside an annular cavity, and they are intrinsically generated inside the cavity through a particular medium. If the cavity experiences a rotation, a frequency shift will take place (Juang & Radharamanan, 2009).

In one of the most popular configurations, the body of RLG is made from a triangular glass block (see figure 3). The glass body is drilled to create air channels, and each corner of the triangular block is placed with glass to create a triangular optical resonator. A high voltage electrical discharge is applied through the anodes and cathodes to pump the optical cavity to create the counter-propagating laser beams that resonate at the same frequency. The angular velocity is then detected by reading the frequency change of the interference pattern created by the counter-propagating beams (Passaro et al., 2017)

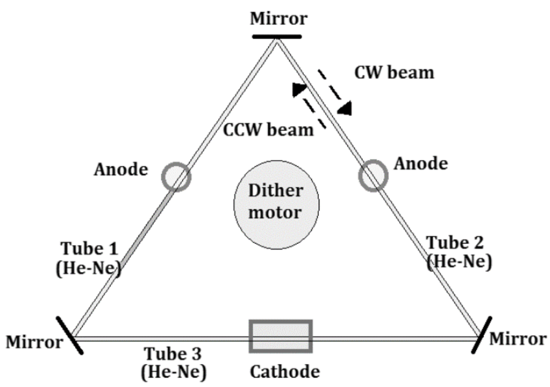

Figure 3: Ring Laser Gyroscope (Passaro et al., 2017)

2.3.1 Critical Parameters for RLGs

Passaro et al. (2017) identified the critical parameters for RLGs:

- Size: A larger ring laser gyro is needed to be made, as the sensitivity of large ring laser gyroscopes increases quadratically with the size of the optical cavity to allow lower rotation rates.
- Mirrors: It is essential to install the mirrors as it is significant for focusing and directing the laser beams throughout the cavity.
- Stability: The body of the gyroscope demands its construction within a substance that has minimum changes with reference to temperature fluctuations.
- Gas: Helium-Neon are the gases that are able to generate the beams that have the most suitable features for the RLG.

Although the RLGs cover the high-performance market, their size and weight remain limiting factors. To counter the issue, miniaturisations take place, but it reduces the reliability of RLG. Hence, this solution did not achieve commercial diffusion. RLG also demands high power sources to operate due to its configuration and working principle.

2.4 FIBRE OPTIC GYROSCOPE (FOG)

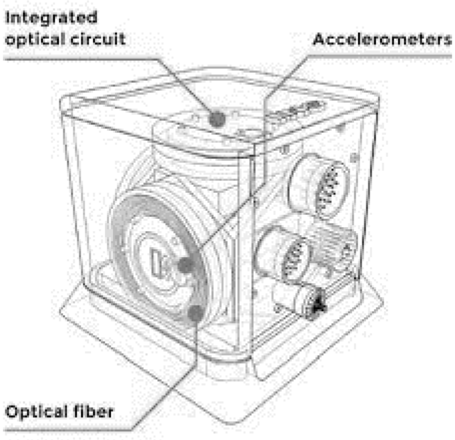

Figure 4: Fibre Optic Gyroscope (iXBlue insight, 2020)

A Fibre Optic based Inertial Navigation System contains three discs of gyroscopes, each of them measures the motion in three axes, the *x*-axis for the pitch, the *y*-axis for the yaw, and the *z*-axis for the roll (Lefèvre, 2012). Applying the Sagnac Effect, a Fibre Optic Gyroscope (FOG) is a passive system that utilises light to measure and calculate the motion in its respective axis. Whenever a motion in any particular axis occurs, it is measured by the phase difference of two identical beams propagated in the same path but opposite direction when they both undergo interference (Lefèvre, 2012). The beam that moves in the same direction as the motion will then have a longer path to travel prior to colliding with the other beam that travelled comparatively shorter, which is the cause of the phase difference.

The performance of FOG can be enhanced by altering the diameter and the length of the fibre optics cables in the gyroscope. However, to improve the accuracy of measurements, a more extensive configuration is necessary (Lefèvre, 2013). Hence, to further increase its performance, technological limits need to be pushed so that the same performance can be maintained even while reducing the size of its configuration, and this allows FOGs to give an unrivalled performance without adding more sensors, unlike any other gyroscopes.

2.4.1 Configuration of a FOG

FOG possesses a long lifetime and high reliability, together with its remarkable performance, as it is based on the solid-state technologies of the optical fibre communications systems (Lefèvre, 2012).

According to Lefevre (2012), FOG is composed of several configurations:

- A broadband source based at a wavelength of 1550nm with Erbium-Doped Fibre Amplifier (ADFA) technology.
- A fibre coil that preserves polarisation ranges from a few hundred metres for medium grade to several kilometres for a high grade).
- An integrated-optic Lithium niobate with electrodes produces phase modulation and generates great polarisation selectivity.
- A fibre coupler sends beams to the returning detector light from the same input-output port of the interferometer.
- An analogue-digital converter that converts the detector signal’s sample.
- A digital logic electronics that functions as the phase modulation generator and phase feedback

Significantly, the performance of a FOG is reproducible in production as long as it abides by adequate design and components in order to ensure its functions.

2.4.2 Difference between RLG and FOG

Similarly, both RLG and FOG work on the Sagnac Effect principle. The significant difference between the two of them is the construction. An RLG uses lasers that propagates through a system of mirrors to determine the object’s motion instead of a simple fibre coil in FOG. To allow the lasers to be dithered, RLG needs to be filled with gas or mechanically vibrated to help lock-in effect from taking place (Advanced Navigation, 2020). RLG also demands an extremely high manufacturing accuracy, particularly on the system of mirrors in its construction.

Despite operating on the same principle and offering exceptional accuracy, the older RLGs are prone to damage due to their construction; hence more maintenance is necessary. These, generally, have a higher cost. Comparatively, FOG is a solid-state system that does not need any dithering mechanism that produces vibrations, allowing it to become more reliable and durable than RLGs. In addition, FOGs reliability and accuracy can be further enhanced by altering the diameter and length of the fibre optic coil used in the construction (Advanced Navigation, 2020).

2.4.3 Performance of FOG

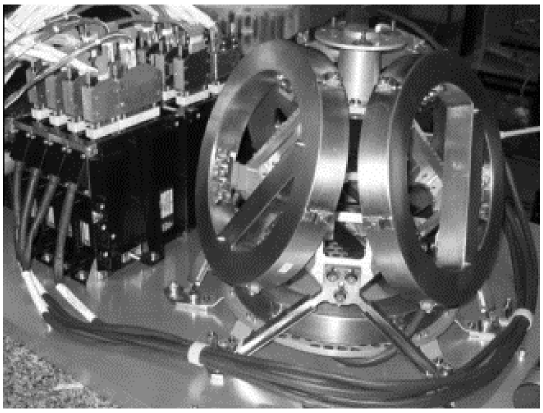

Figure 5: IXBlue FOG (Lefèvre, 2013)

FOG is a field-proven technology that offers exceptional accuracy and reliability, and this is why more than 50 of the world's navies are employing this technology on their platform, from submarines to their first-rate frigates (*IXblue Insights - Fibre-Optic Gyroscopes*, 2020).

FOGs are reliable even in a harsh environment due to their settings that operate with a major shock and vibration, and this makes FOGs the unrivalled choice for parts of the world where navigating is complicated, such as the polar regions (*IXblue Insights - Fibre-Optic Gyroscopes*, 2020).

FOGs are also robust at great water depth, and this is why roughly 80% of the underwater vehicles in the oil and gas industries rely on FOGs for navigation. Compared to mechanical gyroscopes, FOGs are a solid-state system with no moving parts, making its operation silent and reaching up to 400,000 hours of maintenance-free operation (*IXblue Insights - Fibre-Optic Gyroscopes*, 2020). This makes FOGs ideal for long-term and strategic applications such as in the space industry, where FOGs are utilised in high-profile satellite missions, offering outstanding performance for both civil and defence applications. FOGs are significant in defining positions accurately as well as keeping everything in the course.

2.4.4 Example of FOG: Octans by Photonetics

Photonetics has been producing and developing FOGs for roughly fifteen years, fulfilling diverse requirements, mostly in space and military aspects (Gaiffe et al., 2000). The company recently introduced a fibre optic gyrocompass with an integral motion sensor suitable for marine applications. It is then announced as "Octans" and is able to feed complete altitude data of the vessel in terms of its true heading, rates of turns and six degrees of freedom. Octans has an ultra-compact configuration, consumes a small amount of power during operations and is independent of external data input since it is thoroughly inertial in operation, making it the ideal option for the underwater environment (Gaiffe et al., 2000). Due to this particular reasoning, Phonetics has innovated two underwater configurations, dedicated to 1,000 m in depth (Octans 1000) and 3,000 m in depth (Octans 3000).

A single FOG only measures the instantaneous rotation along its coil's main axis; hence, three FOGs are installed to measure the vector from all axes completely. The three gyro meters are combined with another set of three accelerometers to form the Inertial Measurement Unit, the pillar of any inertial reference system. Accelerometers allow significant measurements to be taken, mainly the acceleration along its particular axis, where speed and position will be determined through successive integration—secondly, the information of the apparent local gravity (helps determine the local vertical axis). The requirements for the north finding properties of FOG are complex as it needs to withstand random movements that may be violent instantaneously. The difficulty becomes more apparent due to the disturbance in measuring the terrestrial rotation caused by high rotational values higher than Earth's rotation rate (Gaiffe et al., 2000).

Another factor is that the measurement of gravity is jeopardised by the centrifugal acceleration that might be relatively high (Gaiffe et al., 2000). To counter these issues, Octans abandon the direct use of measuring Earth's rotation rate to relate to the gyroscopic frame and relate the frame to a "fixed" reference frame instead, The Inertial Space. The measurement from the triad of the gyroscopic frame and the accelerometers provides the sum of acceleration and apparent gravity, measured from the motion of the object, which is later compared to the Inertial Space, and the comparison will then be computed. After computing has been done, "observing" the slow drift of apparent gravity caused by the Earth's rotation becomes possible (Gaiffe et al., 2000).

The complete Octans system is configured in a box of less than 6 litres in volume, which is significantly smaller than mechanical gyrocompasses. Furthermore, Octans can be started up while at sea, and it is capable of finding North in less than 5 minutes, no matter what the sea conditions are.

2.4.5 Analysis of the Global Fibre Optic Gyroscope Market

The market for FOG is predicted to grow at a significant rate of 3.43% from 2022 to 2029 (Fiber Optic Gyroscope Market – Global Industry Trends and Forecast to 2029, Data Bridge Market Research, 2021). One of the main reasons for this growth is the rise in the military budget that allows more extensive research for FOG development. Another significant factor is the adoption of automation technologies in homes and industries. Furthermore, the constant development of remotely operated vehicles demands inertial sensors to monitor their attitude and orientation. Despite the rising growth, the introduction of micro-electromechanical systems gyroscope acts as an impedance that might propel the need to develop the fibre optic gyroscope further to help it survive in the market.

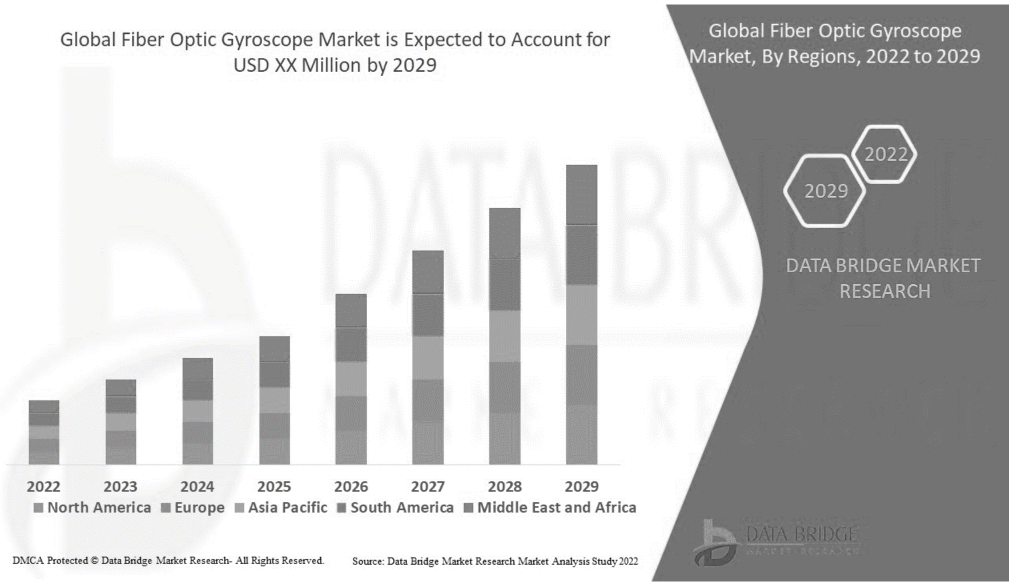

Figure 6: Global Fibre Optic Gyroscope Market Expectation (Fiber Optic Gyroscope Market – Global Industry Trends and Forecast to 2029, Data Bridge Market Research, 2021)

2.5 INERTIAL NAVIGATION SYSTEM

Inertial Navigation System (INS) is a system that determines and calculates the orientation of the position of a moving object and its velocity (Gaiffe et al., 2000). This system is used in a plethora of different vehicles, from outer space all the way to the depth of the ocean, and it is also embedded in some mobile phones for the purpose of location precision and tracking (Wan Bejuri et al., 2019).

The vessel is free to rotate in three dimensions in a seagoing vessel, creating its six degrees of freedom. INS measures these three-dimensional rotations, which are classified as pitch, roll and yaw (Gaiffe et al., 2000). To assess the rotations, INS utilises gyroscopes for all the dimensions, while accelerometers are used to sense the motion and the acceleration of the movement. Although all kinds of gyroscopes are applicable for INS, in terms of efficiency, optical ones remain superior to mechanical tuned-motor gyroscopes (Gaiffe et al., 2000).

Inertial Navigation is one of the basic forms of navigation. It is the only form requiring external references, besides Dead Reckoning, Pilotage, Radio Navigation and Celestial Navigation (Tampere, 2021). The basic principle of the inertial navigation system is the ability to modestly measure the acceleration of the object in certain three-dimensional axis (x, y or z), making it possible to calculate the change in velocity by executing continuous mathematical integration of the acceleration with respect to time (Tampere, 2021). An INS is configured with:

- An Inertial Measurement Unit (IMU) that measures the acceleration and motion of the object
- Instrument support electronics
- Navigation computers calculate the acceleration and motion to determine the attitude of the object.

There are many different designs of INS that possess different performances according to their characteristics, but they can mainly be generalised into two categories; gimbaled or stabilised platforms and strap down configuration. The main differences between these two categories are in terms of their cost, size and reliability. Strap down configuration attaches the sensors rigidly to the body of the vehicle while the stable platform techniques isolate the whole system from the vehicle's body. This configuration has a reduced size, lower cost and greater reliability compared to the stabilised platform configuration. However, the only disadvantage is the increasing complexity of the necessary computation.

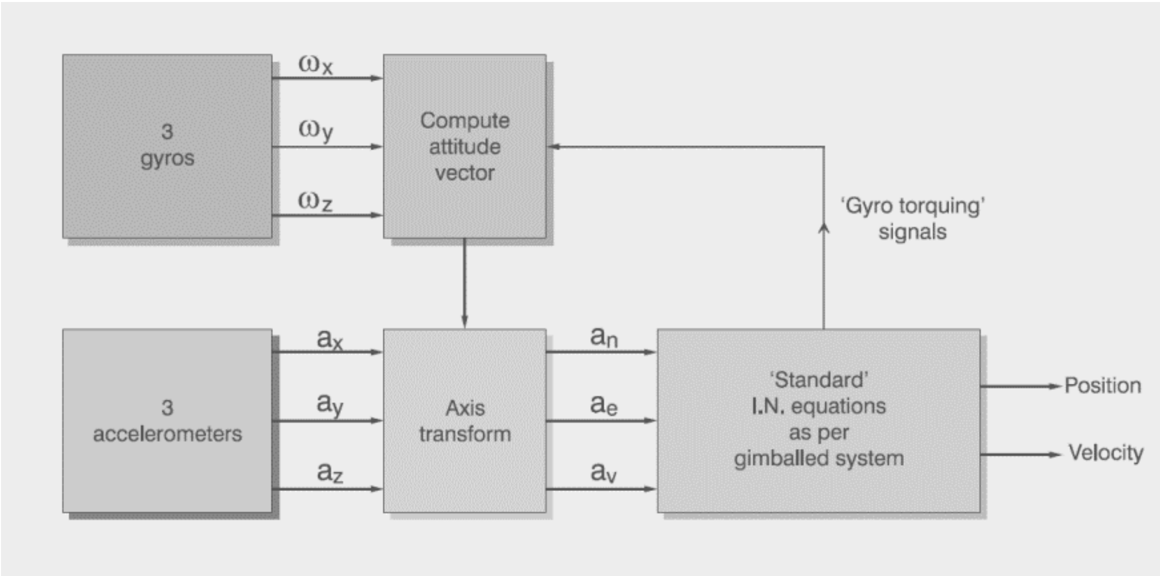

Figure 7: Strap down Inertial Navigation Unit Block Diagram (Tampere, 2021)

In a strap down configuration, three optical gyroscopes are installed together with three accelerometers for each dimensional axis (see figure 5). The triad of gyroscopes will detect the angular velocity of the rotation of the object to determine its direction, while the accelerometers will determine the rate of movement of the object. Upon complex calculation, the position and velocity of the object in all three-dimensional axis (roll, pitch, yaw) will be determined.

There are, however, certain configurations that only utilise the dual-axis rotational laser gyro in its INS. However, due to the angular motions of the vehicle, error modulation effects are prone to occur. To prevent such errors, the method of isolating the vehicle's angular motion using attitude feedback is then developed (Huiying et al., 2021). The principles of error modulation in the rotation process are first analysed based on the error equations of INS. The navigation results and the controlled angular velocity imposed on the rotating mechanism are then investigated to establish a relationship. Finally, various forms of the simulation models of angular motions are then established (Huiying et al., 2021). Based on the study of Huiying et al. (2021), the simulation results prove that this method can successfully isolate the angular motions of the vehicle, thus reducing the influences of angular motions on the modulation's rotation, which significantly improves the navigation's accuracy. Some configurations integrate both optical gyroscopes and rotating modulation technology (Lu et al., 2021).

2.5.1 Examples of FOG-based INS: Boreas by Advanced Navigation

Advanced Navigation is a company that develops remarkable, industry-leading robotics and navigation technologies for the application in the air, land, sea, as well as space. They envision driving the autonomy revolution with AI-powered systems that can deliver unrivalled performance and capabilities, and one of their latest inventions is Boreas, the first fully digital FOG in the world (Advanced Navigation, 2021).

Figure 8: Boreas (Advanced Navigation, 2021)

Boreas is a strategic-grade INS with ultra-high accuracy, and it offers a 40% reduction in terms of SWaP-C (size, weight, power and cost) compared to other competing systems (Advanced Navigation, 2021). It is the first released product manufactured based on Advanced Navigation's newly developed digital FOG. Boreas is an unrivalled competitor for any operations that demand constant availability, ultra-high accuracy orientation and navigation, and this includes surveying subsea, marine, robotics, aerospace and also space. The newly installed FOG in the Boreas features ultra-fast gyro-compassing as it takes only 2 minutes to obtain the heading, whether in stationary motion or while moving (Advanced Navigation, 2021). To calculate the data, Boreas utilises Advanced Navigation's revolutionary sensor fusion algorithm that is significantly intelligent than the other competing systems, and it is able to extract more information from the data measured. The hardware and the system's software are designed and put to trial to reach safety standards to ensure its reliability and robustness.

To achieve such a feat, the FOG that is used in Boreas is complimented with three distinguished yet complementary technologies (Advanced Navigation, 2021):

1. Digital Modulation Technique: This technique allows the errors in the system to be precisely measured and then removed from the measurements. The techniques make the system significantly more stable and reliable than the traditional systems.

2. Revolutionary Optical Chip: By combining and complimenting five sensitive components into one single chip, all the fibre splices used in the traditional FOG can be removed. This technology reduces the size, weight, and power considerably while significantly increasing the system's performance.

3. Specially Designed Optical Coil: The digital system of FOG uses a specially designed closed-loop optical coil, allowing full advantage of the digital modulation techniques

to be utilised. This technology also provides extra protection for the optical components from shocks and vibrations.

3.0 CONCLUSION

As the whole world thrives to achieve a new era of science and technology, the maritime industry is an essential sector for this goal to be achieved. Seafarers must push through their limits to make the maritime industry standstill and invulnerable in all situations.

The constant development of the optical gyroscope has proven to be an ingenious method to be applied in the Inertial Navigation System. Despite having multiple different configurations, an optical gyroscope is still an unrivalled choice in terms of its reliability and performance due to its smaller size, lighter weight, lower consumption, and lower manufacturing and maintenance cost than the mechanical gyroscope.

The Inertial Navigation System is a significant technology utilised in all types of vehicles, from submarines in the deep ocean to satellites in space, all for its ability to precisely define the vehicles attitude and orientation without any external references. In order to achieve such a feat, myriad technologies are constantly developed, from the usage of mechanical gyroscopes to the application of optical gyroscope and even integrating both of them to obtain an ultra-high accuracy measurement.

However, the application of optical gyroscopes is more favourable due to their reliability and performance, and the global expectation market portrays this in the application of Fibre Optic Gyroscope in the 2020s. To ensure the relevance of optical gyroscopes in the industry, constant development and research are compulsory to increase its capabilities further. The errors and flaws of current technologies need to be investigated to obtain the cause of errors, allowing developers to come up with a way to tackle the issues effectively.

The optical gyroscope system can be integrated with a plethora of other systems to derive a more remarkable technology. The same thing goes for the Inertial Navigation System that can be further utilised with other navigational systems such as GPS and Integrated Navigation System.

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