HIGHLY COMPACT FIBER OPTIC GYROCOMPASS FOR APPLICATIONS AT DEPTHS UP TO 3,000 METERS

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Abstract- Octans is a fiber-optic gyrocompass with an integral motion sensor developed by Photonetics for demanding marine applications. In contrast with conventional gyrocompasses relying on a spinning gyroscope, Octans has no moving parts and utilizes instead three Fiber Optic Gyroscopes (FOG) and three quartz accelerometers. The FOG technology is based on the relativistic Sagnac effect: light travels in opposite directions into a fiber optic coil, and interferes at the output with a phase-shift proportional to the rotation rate. Moreover, three accelerometers measure, after Schüler filtering, the local gravity vector. As the FOGs are enough accurate (typically a bias stability of 0,05 °/h), the observation of the gravity slow drift in the inertial space allows one to determine the Earth axis, thus the North direction. In addition, the real three-axis architecture allows Octans to act as a marine motion sensor and compute the complete attitude of the vessel in terms of roll, pitch, heave, surge and sway. Because of a specific algorithm, Octans is able to find the true heading without any help in three minutes even at sea. This system is obviously ideal for ROVs and AUVs applications: low power consumption, compact, light box and very low settling time

INTRODUCTION

The marine gyrocompass is one of the oldest gyroscope-based systems in existence: a rapidly spinning top can align its angular moment with the angular moment of the turning Earth [1] just as a compass will align its magnetic moment with the terrestrial magnetic field, thus defining an orientation (heading) in relation to geographical North. The system has been used since the 1920s by all ships above a certain size when there is a need for data on their heading to an accuracy of a few tenths of a degree and without the risk of magnetic interference. The technology has not changed in any basic way for the last sixty or so years, and it is highly maintenance-intensive and offers limited reliability in terms of use life.

However, there is an ever-increasing demand for precise information on the attitude of the vessel for applications of "survey" type. These requirements for dynamic position data notably relate to the use of sonar arrays, accurate pointing of satellite antennas and the control of ROVs and AUVs.

Usually, these demands for positional reference data requires not only information on true heading, but also complete data on attitude (roll, pitch, heave, surge, sway, etc.). At the present time, this requirement is satisfied to a large extent by associating a "conventional" gyrocompass with a motion sensor. In the specific case of underwater applications, the disadvantages of "conventional" gyrocompasses become even more marked: they are difficult to transport, they are both cumbersome and heavy, their power consumption is significant (a fact relevant to AUV applications, for example), take several hours to start up, and offer only limited roll and pitch angles.

For twenty years or so now, civil and military aeronautical applications have abandoned the use of mechanical gyroscopes in favor of more modern technologies, eliminating the use of gimbals: the navigation or attitude detection platform is in this case directly bound to the structure of the mobile, using so-called "strapdown" technologies [2]. Since such technologies use few or no moving parts, the advantage of strapdown systems compared with those mounted on gimbals are obvious: they are more robust and require less maintenance. The gyrometric sensors used in this context must offer a very wide dynamic range and withstand very severe mechanical environments. Mechanical gyroscopes are therefore replaced by "optical" gyrometers: RLGs (Ring Laser Gyroscopes) or FOGs (Fiber Optic Gyroscopes).

Photonetics has been developing and manufacturing FOGs for approximately fifteen years now for a diversified range of requirements, notably in the military and space fields [3]. Two years ago, the company presented a fiber optic gyrocompass with an integral motion sensor [4] for marine applications. This system has been designated "Octans" and provides complete attitude data: true heading, roll, pitch, heave, surge, sway, rates of turns...

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Octans is ultracompact (it is currently the smallest available gyrocompass), consumes very little power and needs no external data input since it is completely inertial in operation, all of which makes it the obvious positional reference solution for underwater environments. For this reason, Photonetics has developed two underwater housings, one dedicated to applications at depths of up to 1,000 meters (Octans 1000) and the other for applications at depths up to 3,000 (Octans 3000).

We explain the technology of fiber optic gyroscopes below, before going on to describe the architecture and operation specific to the Octans system. We then detail the performance characteristics of the Octans 1000 and 3000.

1. THE TECHNOLOGY OF FIBER OPTIC GYROSCOPES (FOGs)

FOGs do not use the rapidly spinning top employed in mechanical gyroscopes – in fact, they have no moving parts at all. They do not use the gyroscope effect to measure the rotational speeds of mobiles, but a radically different phenomenon – the so-called "Sagnac Effect".

1.1. The Sagnac Effect

The Sagnac Effect is a physical phenomenon of relativistic type; understanding it requires a good grasp of Special Relativity [6]. However, it is possible to provide a simplified (although inaccurate) physical interpretation of the effect. Imagine a coil of optical fiber. Optical fiber, as is well known, is a good vector for the propagation of light. This coil will in principle have two exits at the two ends of the fiber. If we inject a light pulse into one end, it will come out at the other after a duration equal to the time the light takes to cover the entire length of the coiled fiber. If we now inject two pulses simultaneously into the two ends of the coil, they will travel in opposite directions, pass each other in the middle and come out at opposite ends of the coil. The time the light takes to travel through the coil will be the same irrespective of its direction of travel, and the two pulses will therefore exit the fiber at the same time. If we now imagine that the coil is rotating around its central axis, this movement will "help" one pulse but "hold back" the other. It can be seen therefore that the two pulses will leave the coil at different times. If we measure this temporal difference, we can deduce from it the speed of rotation.

1.2. FOG description and performance

In practice, this difference is determined in optics using interferometry, which provides a measurement of the phase difference between the two light waves travelling in opposite directions within the coil. The interferometer is created by "closing" the coil on itself using an optoelectronic component called an "Integrated Optical Circuit" (see figure 1).

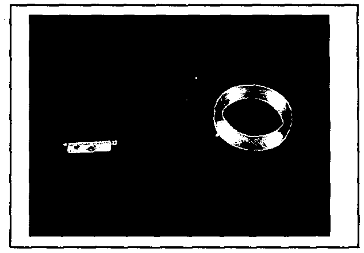

Figure 1 : The "heart" of a FOG / the optical fiber coil with its integrated optical circuit

The ingenious signal processing which follows requires a large number of optoelectronic components if the information on optical phase, carrying information on rotation, is to be converted into a digital signal useable by a calculator. It would be superfluous to go into the technological detail here, but for a complete description of FOG architecture and operation, the reader is referred to bibliographical reference [7], among others.

In practice, FOG performance gets better as it gets bigger, a fact which can be easily understood in terms of the length of the coiled optical fiber: at any given rotational speed, increased length will make it easier to separate the two light pulses temporally in the way described above.

FOG performance can be measured in terms of many parameters, of which the most important is known as bias stability, which means the stability of the zero point, or the intrinsic accuracy of the measurement of rotational movement. It is now usual to express bias stability in degrees per hour (deg/hour), to make comparison easier with the Earth's rotation rate, which is 15 deg/hour (1 revolution in 1 day, 360 degrees in 24 hours, giving 15 degrees per hour).

At Photonetics we produce two types of FOG: one uses a 500-meter coil to obtain a bias stability of 0.1 deg/hour (FOGs 70), and the other a 1000-meter coil for bias stability of 0.01 deg/hour (FOG 120).

In practice, in order to measure the bias stability of a FOG, we measure the Earth's rotation rate. Figure 2 provides an example of the recording from a FOG 120. The FOG must in this case measure 11.33 deg/hour, which corresponds to the projection of the rotation of the Earth onto the apparent vertical at the latitude of Paris (France).

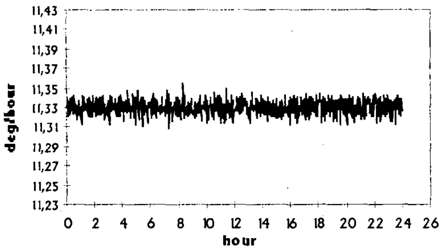

Figure 2 : Bias stability of a FOG 120

1.3. Inertial Measurement Unit (IMU)

In fact, a single FOG measures the projection of the instantaneous rotation along the main axis of its coil, and three FOGs are necessary to measure the rotation rate vector.

This triad of gyrometers is usually combined with a set of three accelerometers. An accelerometer enables measurement firstly of the instantaneous acceleration along a given axis (and thereby, through successive integrations, speed and position), and secondly, knowledge of apparent local gravity, and thereby the local vertical axis.

The compact assembly formed by the three gyrometers and the three accelerometers is called an "Inertial Measurement Unit" (IMU) and forms the heart of any inertial reference system. When an IMU is coupled to a calculator and an interface, the result is an "inertial reference system".

Octans is an inertial reference system capable of providing complete information on the physical attitude of the mobile. The IMU comprises three FOGs (0.1 deg/hour bias stability) and three accelerometers (± 500µg). The internal workings of the Octans are shown in Figure 3.

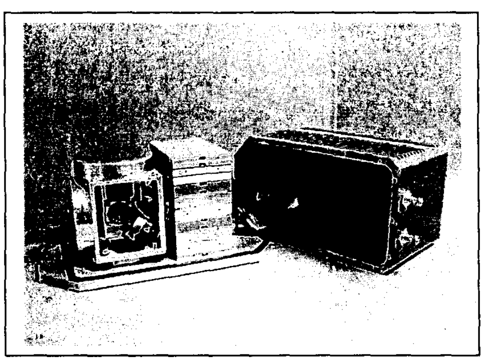

Figure 3 : Open Octans

2. THE FIBER OPTIC GYROCOMPASS – UNDERLYING PRINCIPLES

By definition, a gyrocompass is a gyroscope-based system for the measurement of true heading, that is to say, angular measurement of a position in relation to geographical North, whatever the movements made by the object on which the gyrocompass is placed. This means for example, that the gyrocompass must remain relatively insensitive to pitch and roll movements, which may be at high levels on certain ships. In this way, the gyrocompass is to be distinguished from North finders, which need to remain totally immobile in relation to the Earth when the measurement is done.

Gyrocompass types currently in use comprise a gyroscope which aligns its angular moment with that of the Earth and therefore exploit at a basic level the intrinsic properties of rotating solids, and notably the principle of gyroscopic spins. A gyrocompass using FOGs must therefore be based on a radically different concept. It is this concept that we explain below.

2.1. North finders

We can begin by assuming that our initial objective is to produce a "static" indicator of North, that is to say, an indicator without any mechanical system (which means that we cannot rotate a single horizontal-axis gyro in order to find the position which cancels out the signal, which will correspond to the East). In order to measure the rotation vector of the Earth **Ω**, the first thing we need is three gyros for the three spatial axes. However, that is not enough yet to indicate a heading, because we lack information about the horizontality of the assembly. This information can be obtained from a plumb line (why not ?), electrolytic levels or accelerometers, by making a measurement of the local gravity vector **g**. It then remains to project the Earth rotation vector **Ω** onto the horizontal plane orthogonal to **g** to obtain the direction of geographical North (figure 2). It can be seen that the intrinsic accuracy of this measurement depends on the accuracy of the sensors (the bias of the gyros b_{gyro} and the accelerometers b_{acc} for example) and the latitude L. It can be expressed in radians as [8]:

$$\Delta\Phi = \frac{b_{gyro}}{\Omega} \operatorname{Sec} L + \frac{b_{acc}}{g} \tan L$$

In order to achieve a North finder capable of rivaling commercially available conventional gyrocompasses, accurate to a few tenths of a degree of the secant of the latitude, it is necessary to select gyros offering accuracy to one-hundredth of terrestrial rotation rate (0.1 °/h), such as the FOG 70 we produce, and accelerometers precise to one-hundredth of apparent gravity, specifications which can in fact be met by relatively low-cost accelerometers. In practice, the accelerometers used in our gyrocompass provide better performance than this in order to improve dynamic stability.

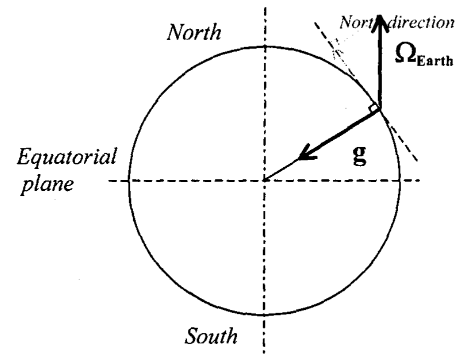

Figure 4: North Finder / basic concept

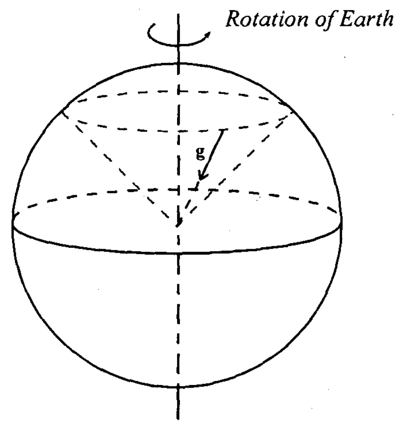

Figure 5: Conical movement of the local gravity g in relation to the Inertial Space

2.2. Gyrocompasses

The gyrocompass represents a step up from the above in terms of complexity. At this level, the system has to withstand random movements – which may be violent, such as a ship's pitch and roll. The difficulty is twofold compared with the previous design: firstly, measurement of terrestrial rotation is disturbed by enormously high rotational values (several orders of magnitude greater than the Earth's rotation rate), and secondly, measurement of gravity is disturbed by centrifugal accelerations which may also prove to be relatively high.

The basic idea is therefore to abandon the direct use of the measurement of the Earth's rotation rate related to the gyroscopic frame, in favor of a "fixed" reference frame, which is in fact the Inertial Space.

Described briefly, the system comprises three gyros and three accelerometers: the three gyros enable the rotation rate of the moving object to be measured at any given instant (including the Earth's rotation rate), and the three accelerometers give the sum of the acceleration and apparent gravity; these measurements are both related to a reference bound to the moving object itself. The angular attitude of the moving object compared to the Inertial space is then computed by integration of the rotation rate. The accelerometer data, which is the sum of the acceleration and gravity, is then expressed within the Inertial Space. After filtering out the acceleration values, it is possible to "observe" the slow drift of apparent gravity due to the rotation of the Earth. In fact, it is easy to show that the apparent gravity expressed within the Inertial Space defines a cone whose main axis is the rotational axis of the Earth (see figure 3). Examination of the movement of **g** can therefore tell us where geographical North is without need of an external reference.

2.3. Performance levels achieved and test results

We produce fiber optic gyrocompasses under the "Octans" designation based on the above concept and comprising three FOGs. Real-time computation is made possible by a DSP-type chip. The complete system is housed in a box with a volume slightly less than 6 liters, which should be compared with mechanical gyrocompasses, which are at least ten times more cumbersome. Our gyrocompass is also capable of being started up while at sea, which is impossible with conventional gyrocompasses. **It finds North in less than five minutes whatever the sea conditions**. The performance obtained is perfectly comparable with that offered by conventional gyrocompasses, with a heading stability better than 0.5 deg.sec(L) (sec L = 1/cos(L))
Its static and dynamic heading stabilities are shown in figures 4 and 5 respectively. The dynamic heading stability measurement was performed by DCI Maritec B.V. (The Netherlands) in February 1999.

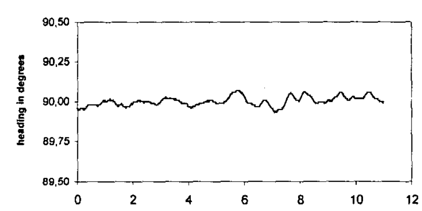

Figure 6 : stability of heading in static conditions (90 deg true heading)

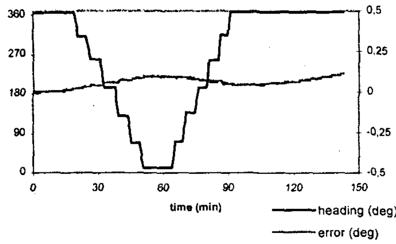

Figure 7 : stability of heading in dynamic conditions

3. THE MOTION SENSOR: UNDERLYING PRINCIPLES

3.1. Octans is also a motion sensor

A motion sensor provides information on vessel attitude. This information is partly angular in nature – yaw, roll, pitch – and partly "metric" – heave, surge and sway. Given that Octans is really an inertial system, it is obviously capable of providing all this information. In this case, yaw is referenced to North because of availability of the gyrocompass mode, and for this reason, unlike conventional motion sensors, there is no yaw drift. Information on heave, surge and sway is in fact computed from acceleration data twice integrated and filtered around the continuous in order to subtract accelerometer bias.

3.2 Achieved performance levels and test results

Static stability of roll and pitch angles is directly dependent on the stability of accelerometer bias. The accelerometers used offer a stability better than 500 g, which means that the stability of roll and pitch is better than 0.03 deg, as long as the ship's acceleration is correctly filtered in order to avoid any additional dynamic error. In practice, horizontal acceleration, due in large part to changes in the heading of the ship, can be satisfactorily filtered with Octans without "heave compensation", unlike conventional motion sensors. An example of roll stability is shown in figure 6 (measurement performed by Maritec B.V.). It can also be seen that the basic principles underlying the design of the Octans mean that it has no limits on roll and pitch angles – it can even be started up upside down!

Performance in the measurement of heave, surge and sway is generally specified both in centimeters and as a percentage of a defined frequency domain. Performance expressed in centimeters corresponds, broadly, to accelerometer bias processed through the high-pass filter, and performance in percentage terms to high-pass filter rejection at its cut-off frequency.

According to the size of the craft and the precise application involved, users have a choice of filter structure, but typically, as long as the cut-off frequency does not exceed a few hundredths of a hertz, heave, surge and sway performance will be of the order of a few centimeters or a few percent of the dynamic range.

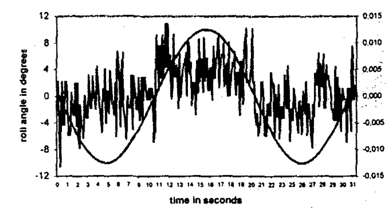

Figure 8 : stability of roll in dynamic conditions

4. OCTANS FOR UNDERWATER APPLICATIONS / OCTANS 1000 AND 3000

4.1. Underwater housings

As we have seen, Octans is an inertial reference system based around FOGs. It behaves in a broadly similar way to a combination of conventional gyrocompass plus conventional motion sensor. The whole system is installed in a very compact package, which in turn brings with it a number of major technical benefits, including ease of transport and installation, 5 minutes' settling time, elimination of the need for heave compensation, and no limitation on roll and pitch angles.

This makes Octans the ideal candidate for underwater applications such as ROVs and AUVs. Photonetics has therefore developed underwater housings, focusing particularly on two types of application: down to 1,000 meters (or 3,280 feet; this is the Octans 1000) and down to 3,000 meters (or 9,840 feet; this is the Octans 3000).

Figure 9 shows an open Octans 3000, with its dimensions compared to those of the CD-ROM delivered with the Octans for configuration purposes.

Figure 9 : Open Octans 3000

4.2. Performance

The performance levels provided by the Octans system – both the Octans 1000 and the Octans 3000 – are summarized in Table I. Overall dimensions are specified in Table II.

Heading accuracy	± 0.5 deg . sec (Lat)
Settling time	5 minutes
Roll and pitch accuracy	0.05 deg
Heave accuracy	2 inches
Operating Temperature	-40 °F / 140 °F
Power consumption	< 15 Watt
Input Voltage	20 to 35 V d.c.

Table I : performances of Octans, Octans 1000 and Octans 3000

	Octans	Octans 1000	Octans 3000
Depth	Sea level / Hermetic package	3280 feet (tested at 120 bar)	9840 feet (tested at 360 bar)
Shape	rectangular	cylinder	cylinder
Dimension	11 in (L) x 5.4 in (W) x 6 in (H)	Φ = 8.2 in x 12.5 in	Φ = 8.2 in x 12.5 in
Material	Aluminum	Aluminum	Stainless Steel
Weight	10 pounds	22 pounds	55 pounds

Table II : The dimensions of the Octans, Octans 1000 and Octans 3000

CONCLUSION

Octans is a fiber-optic gyrocompass with an integral motion sensor developed by Photonetics for demanding marine applications. In contrast with conventional gyrocompasses relying on a delicate spinning-mass gyroscope, Octans has no moving parts and uses instead three 0,1 °/h Fiber Optic Gyroscopes and three quartz accelerometers. This real three-axis strapdown architecture allows Octans to behave as an AHRS : in addition to the true-North heading output, Octans acts as a marine motion sensor and computes the complete attitude of the vessel in terms of roll, pitch, heave, surge and sway, in order for instance, to easily drive stabilisers, point a SatCom antenna or reference a multi-beam sonar system.

Moreover, Octans is a very compact system with a very low power consumption, and exists in two underwater housings for sub sea applications (ROVs and AUVs for instance) : 1000 meters (Octans 1000) and 3000 meters (Octans 3000).

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