ON THE DETERMINATION OF SHIP'S COURSE BY THE LASER GYRO-COMPASS

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***Abstract* – The work presents a particular method on the determination of ship's course by optical fibre laser gyro-compass. The laser gyro-compass qualitatively differs from all the other types of gyro-compasses, so that the angular momentum carrier under the form of a flywheel and the other afferent parts have been given up. The measurement of absolute speed of rotation is performed by two coherent light beams propagating in the opposite directions along a circular outline of optical fibre. Due to the ring rotation, the two rays cover the path in different times, the time difference being directly proportional to the rotation speed of optical fibre ring. Taking into account that the gyro-laser doesn't determine the rotation direction, for determining the ship's course we use three gyro-lasers, each of them determines the component on an axis of rotation.**

Keywords: *laser gyro-compass, determination of ship's course.*

1. THE CONSTRUCTION PRINCIPLE OF OPTICAL FIBRE GYRO-LASER

The laser gyroscope is made of an optical fibre ring of radius R (fig.1.a) in which two monochromatic light rays are propagated in opposite directions with the propagation speed c, starting at once (simultaneously) from the point M.

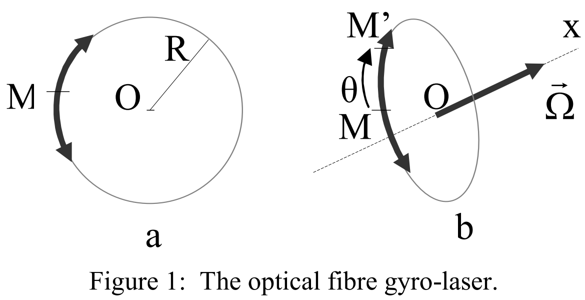

Figure 1: The optical fibre gyro-laser.

The propagation time of the two laser rays is measured by a very sensitive detector also arranged in point M, so that the path travelled by the two rays is the circle circumference, L=2πR and the propagation time is[3]:

$$T=L/c \tag{1.1}$$

At the same time, the ring turns round at the angular speed $\vec{\Omega}$ making the angle:

$$\theta = \Omega \cdot T \text{ ,}$$

or it travels through the length , see fig.1.b.

$$l = R \cdot \theta$$

The ray propagating in the rotation direction of the ring will travel through the distance:

$$L_{+} = L + l \tag{1.2}$$

And the ray propagating in reverse direction of the ring rotation will travel through the path:

$$L_{-} = L - l \tag{1.3}$$

Consequently, the two rays will travel through a difference of distance:

$$\Delta L = L_{+} - L_{-} = 2l = 2R\Phi \tag{1.4}$$

The difference of distance induces a phase difference (shift) of the two laser rays. Considering the wavelength γ, equivalent to a phase difference (shift) equal to 2π corresponding with a path difference ΔL, it will correspond to it a phase shift Δφ of the two laser rays:

$$\Delta\varphi = \frac{2\pi \cdot \Delta L}{\lambda} \tag{1.5}$$

Substituting ΔL from the previous relations, it results:

$$\Delta\varphi = \frac{4\pi RL}{\lambda c}\Omega = \frac{8\pi^2 R^2}{\lambda c}\Omega = \frac{8\pi A}{\lambda c}\Omega \tag{1.6}$$

Where:

A = area of optical fibre ring
R = radius of ring
λ = wavelength of laser rays
c = velocity of light
Ω = angular speed of gyro-laser.

It has been found that the phase shift of laser rays is direct proportional to the angular rotation speed of optical fibre ring.

Taking into account the relations between the difference of time Δt and the frequency difference Δf and between the difference of time Δt and the difference in phase Δφ, we have:

$$\Delta f = f\frac{\Delta t}{t};\quad \Delta t = \frac{\Delta\varphi}{2\pi f};\qquad t = \frac{2\pi R}{c};$$

and considering the relation (1.6) it results:

$$\Delta f = \frac{2R}{\gamma}\Omega = \frac{2A}{\pi R\gamma}\Omega \tag{1.7}$$

It has been found that the frequency difference Δf of laser rays is direct proportional to the angular rotation speed of optical fibre ring.

The optical fibre gyro-laser as a sensor of angular rotation speed has a wide measuring range. The theoretical value of maximum limit of measurement is determined by the band-pass width of the optical fibre ring and the theoretical value of the minimum limit is determined by the width of vibrational spectrum generated by the annular laser. According to some information published in the technical literature, the lower measurement threshold is at 0.001 degrees/hour which satisfy the biggest requirements imposed by the application of gyrolaser in maritime navigation.

2. THE DETERMINATION OF SHIP'S COURSE BY THE OPTICAL FIBRE LASER GYRO-COMPASS

If the vector $\vec{\Omega}$ has any orientation to the measuring axis $\vec{n}$ of the gyro-laser (fig.2), taking into account the relation (10), the output signal can be written:

$$\Delta f = \frac{4A}{L\lambda}\left(\vec{\Omega}\cdot\vec{n}\right) = \frac{4A}{L\lambda}\Omega\cos\alpha \tag{2.1}$$
$$\Delta f = k\Omega\cos\alpha$$

where:

α is the angle between $\vec{\Omega}$ and $\vec{n}$.

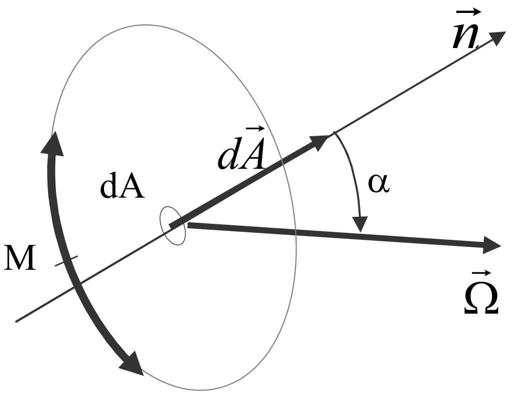

Figure 2 : The rotation of the ring to any direction

The expression (2.1) which states the relation between the frequency variation Δf and the absolute rotational velocity of the optical fibre annular laser is essential for performing the laser gyroscope. By measuring the frequency difference Δf, the relative rotational velocity is determined by the expression:

$$\Omega = \frac{L\cdot\lambda\cdot\Delta f}{4A\cos\alpha} = \frac{L\cdot c\cdot\Delta f}{4fA\cos\alpha} \tag{2.2}$$

Considering the angle α = 0 and integrating the expression (2.2) it is obtained the dependence between the angular displacement variation Δθ of laser and the number n of difference frequency cycles (periods) Δf:

$$\Delta\theta = \frac{L\cdot c}{4f\cdot A}n = \frac{L\cdot\lambda}{4A}n \tag{2.3}$$

The difference frequency Δf also depends on the following parameters of annular laser:

- the relative difference of quality factors of laser rays of opposite direction
- the frequency bandwidth of the resonator
- the position of generating frequency on the atomic spectrum line and
- the intensity difference of rays propagating in opposite direction on the optical fibre ring.

The variations of these parameters generates the instability of resonance frequency.

In general, if $d\vec{A} = \vec{n}\cdot dA$ is the oriented area element, A being the area of the surface limited by the length of the optical fibre ring (fig.2), the relation (2.1) can also be written:

$$\Delta f = \frac{4}{L\lambda}\int_A \vec{\Omega}\cdot d\vec{A} = \frac{4\Omega}{L\lambda}\int_A dA\cos\alpha \tag{2.4}$$

From the relation (2.4) it has been found that if the vector which is to be measured, $\vec{\Omega}$, doesn't coincide with the measuring axis when $\cos\left(\vec{\Omega}, d\vec{A}\right) \neq 1$, then for measuring the vector $\vec{\Omega}$ of any direction, having three orthogonal components $\vec{\Omega}_x$, $\vec{\Omega}_y$, $\vec{\Omega}_z$ it is necessary to use three ring-shaped gyro-lasers having their measuring axes oriented to the axes of trihedron (trihedral angles) Oxyz (fig.3).

If the orientation of the vector $\vec{\Omega}$ to the axes of the reference system Oxyz is given by the angles α, β and γ according to the relation (11) it can be written:

$$\begin{cases} \Delta f_x = k_x\Omega\cos\alpha \\ \Delta f_y = k_y\Omega\cos\beta \\ \Delta f_z = k_z\Omega\cos\gamma \end{cases} \tag{2.5}$$

where:

Δf_x, Δf_y and Δf_z are the useful signals from the three gyro-lasers and k_x, k_y and k_z are the proper proportionality factors.
As:

$$\cos^2\alpha + \cos^2\beta + \cos^2\gamma = 1$$

it results that:

$$\Omega = \sqrt{\left(\frac{\Delta f_x}{k_x}\right)^2 + \left(\frac{\Delta f_y}{k_y}\right)^2 + \left(\frac{\Delta f_z}{k_z}\right)^2} \qquad (2.6)$$

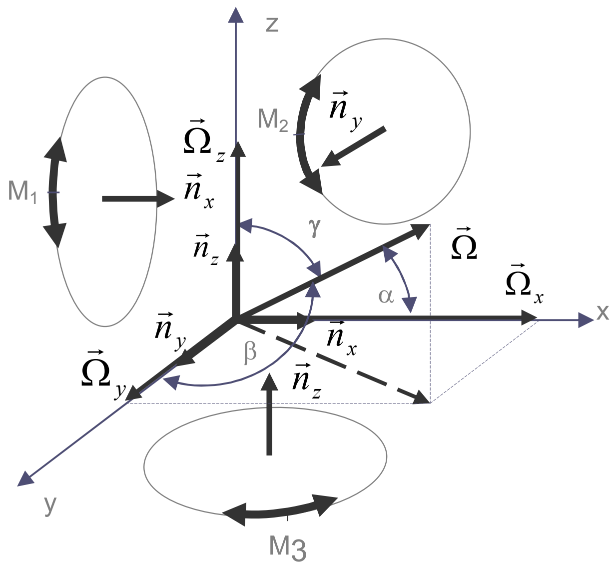

Figure 3 : Gyrometer with three gyro-lasers

The direction of the vector $\vec{\Omega}$ is determined by calculating the angles α, β and γ by means of the relations:

$$\cos\alpha = \frac{\Delta f_x}{k_x\Omega};\ \cos\beta = \frac{\Delta f_y}{k_y\Omega};\ \cos\gamma = \frac{\Delta f_z}{k_z\Omega} \qquad (2.7)$$

The vector $\vec{\Omega}$ represents the vector resulted between the angular velocity of the Earth rotation $\vec{\omega}_t$ and the vector of the ship's angular speed $\vec{\omega}_N$ (figs.4 and 5):

$$\vec{\Omega} = \vec{\omega}_t + \vec{\omega}_N \qquad (2.8)$$

The gyro-laser P_x measures the angular speed on Ox axis,

$$\left(\vec{\omega}_0 + \vec{\omega}_N\right)\cos Dg = \vec{\Omega}\cos\alpha \qquad (2.9)$$

resulting the frequency difference Δf_x :

$$\begin{aligned}\Delta f_x &= k_x \cdot \left|\vec{\omega}_0 + \vec{\omega}_N\right| \cos Dg \\ \Delta f_x &= k_x \cdot \Omega\cos\alpha\end{aligned} \qquad (2.10)$$

The gyro-laser P_y measures the angular speed on O_y axis,

$$\left(\vec{\omega}_0 + \vec{\omega}_N\right)\sin Dg = \vec{\Omega}\cos\beta \qquad (2.11)$$

resulting the frequency difference Δf_y :

$$\begin{aligned}\Delta f_y &= k_y \cdot \left|\vec{\omega}_0 + \vec{\omega}_N\right| \sin Dg \\ \Delta f_y &= k_y \cdot \Omega\cos\beta\end{aligned} \qquad (2.12)$$

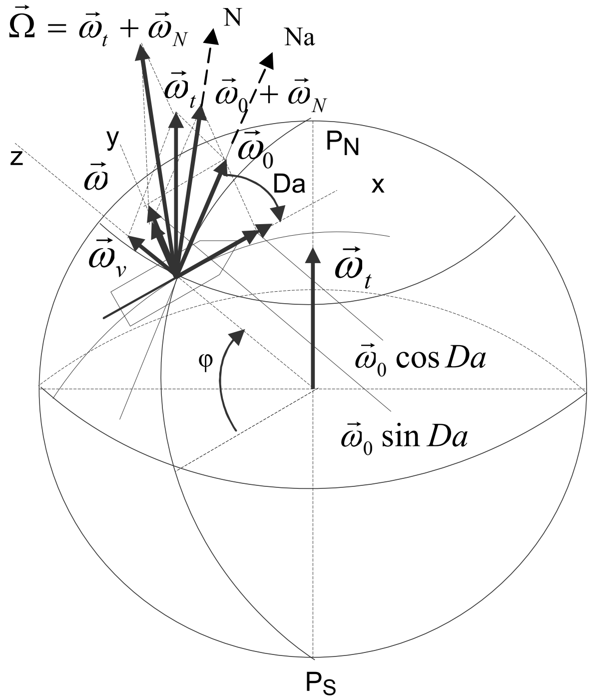

Figure 4 : The angular speed measured by the optical fibre laser gyro-compass

The gyro-laser P_z measures the angular speed on O_z axis,

$$\vec{\omega}_v = \vec{\omega}_t \sin\varphi = \vec{\Omega}\cos\gamma \qquad (2.13)$$

resulting the frequency difference Δf_z :

$$\Delta f_z = k_z \cdot \omega_t \sin\varphi = k_z \cdot \Omega\cos\gamma \qquad (2.14)$$

The modulus of the vector:

$$\left(\vec{\omega}_0 + \vec{\omega}_N\right)$$

is calculated by means of the relation:

$$\left|\vec{\omega}_0 + \vec{\omega}_N\right| = \Omega \sin\gamma \tag{2.15}$$

From the relations (2.10, 2.12, 2.14, 2.15) it results:

$$\cos Dg = \frac{\Delta f_x}{k_x \cdot \Omega \sin\gamma} \tag{2.16}$$

$$\sin Dg = \frac{\Delta f_y}{k_y \cdot \Omega \sin\gamma} \tag{2.17}$$

As a result, the optical fibre gyro-laser indicates the gyro-compass course obtained by solving the expressions (2.16, 2.17):

$$\begin{cases} Dg = \arccos \dfrac{\Delta f_x}{k_x \cdot \Omega \sin\gamma} \\ Dg = \arcsin \dfrac{\Delta f_y}{k_y \cdot \Omega \sin\gamma} \end{cases} \tag{2.18}$$

3. CONCLUSIONS

The particular interest in the optical fibre laser gyro-compasses is explained by their special qualities and performances. Among their qualities we have to mention the absence of the angular momentum carrier under the form of a rotor, the absence of suspension, of bearings and of other mechanical moving parts. Under these conditions, the reliability and the accuracy of laser gyro-compasses are higher than those of the classical gyro-compasses.
It must be mentioned that the sensitive elements of laser gyroscopes give out discreet signals which make easier their processing in electronical computers and their coupling with the electronical map systems.
Referring to the fact that the gyrolaser is an unit with a very low power consumption as compared to the classical gyroscope (some watts as against the tens of watts at the classical gyroscopes). On the other hand, the starting time of gyrolaser is of second fraction order, while for stabilized operating conditions of classical gyroscopes there are necessary tens or even hundreds of seconds.
The transitory thermal condition at the classical gyroscopes is much longer, 15-30 minutes, while the transitory condition time of gyrolaser is practically negligible. Also, the meridian orientation of the classical gyrocompass is at least 4-5 hours, while the gyrolaser instantaneously indicates the direction of angular velocity vector measured (the horizontal component of angular rotational velocity of the Earth).
Besides the remarkable qualities of gyrolaser, I have to mention the existence of some technological and practical difficulties, also, the output signal Δf of gyrolaser, under its simplest form, doesn't allow to distinguish the direction in which the measured rotational motion is performed.
Regardless of the rotational motion direction, the signal obtained at the optical fibre gyrolaser output given by the relation (1.7) is unchanged.

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