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Improvement of the theory of ship's motions on gyrocompass operation

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Abstract
The article presents the results of compliance with effects of impact wave course and the resulting orbital motions on the accuracy of the gyrocompass.

Introduction

In stormy weather, when a ship is affected by wave action, the ship's centre of gravity begins to move along a curvilinear trajectory. The movement track is a result of lateral and orbital motions. The influence of lateral motions on gyrocompass accuracy has been studied and described in detail at [1, 2, 3], and the value of rolling deviation caused by such motions (δ_R) for a single gyroscope compass is expressed by the formula:

$$\delta_R = -\frac{B\theta^2\omega_R^4 l^2 \sin 2CC}{4g^2 H\Omega\cos\varphi} \tag{1}$$

where:

- B – module of pendulum moment at gyroscope sensor of the compass;
- θ – amplitude of angle heel;
- ω_R – frequency of rolling motions;
- l – distance between the centre of rolling and sensor;
- g – acceleration of gravity;
- H – kinetic moment of the gyroscope;
- Ω – angular speed of earth's revolving around its axis;
- φ – latitude;
- CC – compass course.

As the value of deviation depends on the doubled compass course 2*CC,* it is often referred to as intercardinal deviation. It assumes maximum values on courses 45°, 135°, 225° and 315°.

It follows from the formula above that if the gyrocompass is in the centre of rolling motions ($l = 0$), deviation does not occur. Such gyroscope positioning would be an ideal solution, but in practice it is impossible because orbital motions also affect the motion centre track.

During orbital motions, ship's centre of gravity moves in the plane of wave propagation, along an elliptical track, or spherical track in a particular case. The phenomenon was investigated and described in detail by A.N. Krylov, who did research onboard the cruiser *Petropavlovsk* [4].

The impact of orbital motions on the cruiser's centre of gravity movement track depending on wave relative bearing (α) and for various ship's speeds (V) is shown in the diagram (Fig. 1).

When the ship is in motion, linear acceleration components j_w and j_s occur, related to the force of inertia. Their direction conforms with the lines of the meridian and the parallel. This phenomenon causes deviations of orbital motions δ_0. The problem has not been discussed in the literature yet. Without examining this phenomenon first, it cannot accurately analyze the effectiveness of methods for reducing the impact of motions on gyrocompass accuracy.

The profile of gyrocompass motion around a point O along a circular trajectory, caused by orbital motions, at frequency ω_R is shown graphically (Fig. 2).

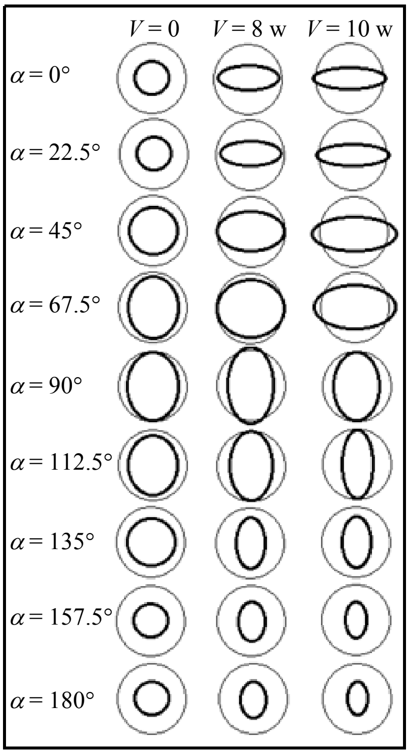

Fig. 1. Impact of orbital motions on the cruiser's centre of gravity track depending on wave relative bearing and various speeds of the ship [4]

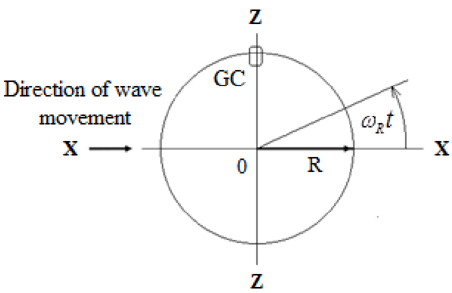

Fig. 2. Gyrocompass motion caused by orbital motions

The gyrocompass displacement due to orbital motions in the direction of wave movement, is expressed by equation:

$$X = r\cos\omega_K t \tag{2}$$

As a result of circular movement an acceleration J_X is created (Fig. 3), consisting of two components: J_W and J_S.

Acceleration in the horizontal direction J_X, along the XX axis (Fig. 3) is determined by the formula:

$$J_X = \ddot{x} = -r\omega_R^2 \cos\omega_R t \tag{3}$$

The force of inertia F_X of gyroscope sensor centre of gravity caused by the acceleration J_X is defined by formula:

$$F_X = M \cdot \ddot{x} = -Mr\omega_R^2 \cos\omega_K t \tag{4}$$

where: M – mass of the gyroscope sensor.

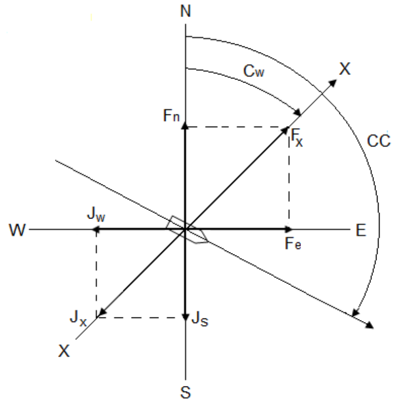

Fig. 3. Accelerations and forces of ship's orbital motions

That forces may be decomposed into two components, F_N and F_W, acting along the axes NS and EW:

$$\begin{aligned} F_N &= F_X \cos C_W \\ F_E &= F_X \sin C_W \end{aligned} \tag{5}$$

where: C_W – the course of the wave.

The acting forces create moments of forces directed along the gyrocompass sensor axes: XX, YY and ZZ.

$$\begin{aligned} L_X &= F_E \cdot a = -Mar\omega_R^2 \cos\omega_R t \sin C_W \\ L_Y &= F_N \cdot a = -Mar\omega_R^2 \cos\omega_R t \cos C_W \\ L_Z &= F_N \cdot a \cdot \sin\psi = -Mar\omega_R^2 \cos\omega_R t \cos C_W \cdot \psi \end{aligned} \tag{6}$$

where:

- r – amplitude of orbital motions;
- t – time;
- $\sin\psi \approx \psi$ – for small values of the angle ψ.

Taking into account the acting moments of forces, we can write the equations of a single gyroscope pendulum type gyrocompass in these forms:

$$\begin{aligned} &H\dot{\alpha} + B\beta = H\Omega\sin\varphi - Mar\omega_R^2 \cos\omega_R t \cos C_W \\ &H\dot{\beta} - H \cdot \Omega\cos\varphi \cdot \alpha = Mar\omega_R^2 \cos\omega_R t \cos C_W \cdot \psi \\ &I\ddot{\psi} + B\psi = -Mar\omega_R^2 \cos\omega_R t \sin C_W \end{aligned} \tag{7}$$

The equations of sensor spin of such compass around the axis XX do not depend on coordinates α and β or their derivatives, and have this form:

$$\ddot{\psi} + q^2\psi = -\frac{Br\omega_R^2}{g}\cos\omega_R t \cdot \sin C_W \tag{8}$$

where:

- q – circular frequency of gyrocompass sensor at free oscillations around the axis XX;
- $B = Mga$ – module of the moment of a pendulum gyroscope sensor.

The most interesting partial solution of the differential equation (8) takes this form:

$$\psi_P = -\frac{q^2\omega_R^2 r}{g(q^2-\omega_R^2)}\sin C_W \cos\omega_R t \qquad (9)$$

Bearing in mind that $q \succ\succ \omega_R$, we can present the formula (9) as:

$$\psi_p \cong -\frac{\omega_R^2 \cdot r \cdot \sin C_W}{g}\cos\omega_R t \qquad (10)$$

The differential equations (7) of the gyrocompass according coordinates α and β, accounting for the solution (10) assume this form:

$$\begin{aligned} &H\dot{\alpha} + B\beta = H\Omega\sin\varphi - Mar\omega_R^2\cos\omega_R t\cos C_W \\ &H\dot{\beta} - H\cdot\Omega\cos\varphi\cdot\alpha = \qquad (11) \\ &= -\frac{Mar^2\omega_R^4}{g}\cdot\cos C_W\cdot\sin C_W\cos^2\omega_R t \end{aligned}$$

Elementary trigonometric transformations of the formulas (6) and (11) permit to write the equation (11) as:

$$\begin{aligned} &H\dot{\alpha} + B\beta = H\Omega\sin\varphi - Mar\omega_R^2\cos\omega_R t\cos C_W \\ &H\dot{\beta} - H\cdot\Omega\cos\varphi\cdot\alpha = \qquad (12) \\ &= -\frac{Br^2\omega_R^4}{4g^2}\cdot\sin 2C_W(1+\cos 2\omega_R t) \end{aligned}$$

The gyrocompass filters high frequency excitations ω_R, but constant components of these excitations cause constant deviations which have the values:

$$\begin{aligned} \beta_P &= \frac{H\Omega\sin\varphi}{B} \\ \alpha_P &= \frac{Br^2\omega_R^4}{4g^2 H\Omega\cos\varphi}\cdot\sin 2C_W \end{aligned} \qquad (13)$$

An analysis of the above formulas leads to a conclusion that the coordinate β_P does not depend on orbital motions or ship's rolling.

The coordinate α_P describes the deviation caused by orbital motions. In this connection we can write:

$$\delta_0 = \prec \alpha_P \succ = \frac{Br^2\omega_R^4}{4g^2 H\Omega\cos\varphi}\cdot\sin 2C_W \qquad (14)$$

One can see there is no method of reducing the deviation from orbital motions, because the orbital motions amplitude r is a function of wave height.

This type of deviation, unlike the deviation from rolling, does not depend on ship's course, but it depends on wave direction course C_W. This means that if orbital motions occur, they affect all ships without exception (regardless of the ship's course).

This quality of orbital motion is the most bad problem of gyrocompass accuracy in case of wave action. It also substantially increases the total value of the deviation caused by ship's motions. This factor has a particularly significant influence on gyrocompass accuracy on relatively small vessels, where strong ship's motions are observed, consequently, the phenomenon of orbital motions is also strong.

For instance can be used the gyrocompass "*Kurs-4*" (single gyroscope), with the following working parameters:

$H = 15.55$ Nms;
$B = 0.657$ Nm;
$\Omega = 7.29\cdot10^{-5}$ s^{-1};
$l = 5$ m; $\theta_0 = 20°$ (0.349 rad);
$\omega_R = 0.5$ s^{-1};
($\tau_R = 12.6$ s) $CC = 45°$;
$\varphi = 60°$;
$g = 9.81$ ms^{-2}.

The deviation from rolling is $\delta_R = 32.9°$. With the above gyrocompass parameters, and an assumed radius of orbital motions $r = 2.5$ m, the deviation from orbital motions $\delta_0 = 67.4°$.

The formula of total deviation δ_S, including deviations of rolling and deviation of orbital motions, has this form:

$$\delta_S = -\frac{B\theta^2\omega_R^4 l^2\sin 2CC}{4g^2 H\Omega\cos\varphi} + \frac{Br^2\omega_R^4\cdot\sin 2C_W}{4g^2 H\Omega\cos\varphi} \qquad (15)$$

The conclusions from an analysis of the formula (15) are as follows:

$$\delta_S = -\frac{B\omega_R^4(\theta^2 l^2\sin 2CC - r^2\sin 2C_W)}{4g^2 H\Omega\cos\varphi} \qquad (16)$$

When a compass course CC and wave course C_W are simultaneously cardinal courses at any combination, the motions deviation equals zero.

When the course C_W is a cardinal course, and a compass course CC is an intercardinal course, the motions deviation equals:

$$\delta_S = -\frac{B\theta^2\omega_R^4 l^2\sin 2CC}{4g^2 H\Omega\cos\varphi} \qquad (17)$$

When the course C_W is intercardinal, but the compass course CC is a cardinal course, then the motions deviation is equal to:

$$\delta_S = \frac{Br^2\omega_R^4\sin 2C_{\mathrm{W}}}{4g^2 H\Omega\cos\varphi} \qquad (18)$$

If the compass and wave courses CC and C_W are intercardinal, the same or opposite, the motions deviation can be written in this form:

$$|\delta_S| = \left| \frac{B\omega_R^4(\theta^2 l^2 - r^2)}{4g^2 H\Omega\cos\varphi} \right| \tag{19}$$

If the intercardinal courses C_W and CC are orthogonal (perpendicular), the motions deviation assumes the maximum of possible values:

$$|\delta_S| = \left| \frac{B\omega_R^4(r^2 + \theta^2 l^2)}{4g^2 H\Omega\cos\varphi} \right| \tag{20}$$

A comparison of all five characteristic combinations of the courses shows that the worst situation occurs when the intercardinal courses CC and C_W happen to be orthogonal. Consequently, the worst course CC and C_W combinations can be briefly presented in the table below:

CC	C_W
45° or 225°	135° or 315°
135° or 315°	45° or 225°

The presented material allows to make a deep analysis of the process of creating gyrocompass motions-induced deviation, which may lead to a development of methods of deviation reduction.

To date, the most effective method of preventing motion-induced deviations has been the one using two-gyroscope sensors.

The deviation from rolling of a two-gyroscope compass sensor [1, 2, 3] may be described by the formula:

$$\delta_S \cong \frac{B\theta^2\omega_R^4 l^2 \sin 2CC}{4g^2 H\Omega\cos\varphi} \cdot \frac{\tau_R^2}{\tau_\psi^2} \tag{21}$$

where:

- τ_R – period of ship motions in waves;
- τ_ψ – period of sensor motions around its main axis XX.

The coefficient (τ_R^2/τ_ψ^2) represents the reduction of ship motion impact on the two-gyroscope compass indications.

Taking into account simultaneous rolling and orbital motions, the formula describing the deviation of a two-gyroscope compass gets this form:

$$\delta_S = -\left[\frac{B\omega_R^4(\theta^2 l^2 \cdot \sin 2CC - r^2 \cdot \sin 2C_W)}{4g^2 H\Omega\cos\varphi} \right] \frac{\tau_K^2}{\tau_\psi^2} \tag{22}$$

Designers state that typical gyrocompasses of "*Kurs-4*" or "*Standard*" type have a motions deviation reduction coefficient equal to 0.0003. It can be mind that such coefficient can reduce the deviation before nearly zero. However, the real compasses at stormy condition has a deviation from 1.5° to 2.5°. It takes place from reason of influence at stormy weather the oil damper [1, 2, 3] and other reasons.

A single-gyro compass, unaffected by ship's motions, still remains manufacturers' and seafarers' dream.

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