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Viktor Stepanenko, Petro Chapchai

ELECTRICAL-NAVIGATION DEVICES

ЕЛЕКТРОНАВІГАЦІЙНІ ПРИЛАДИ

MINISTRY OF DEFENSE OF UKRAINE

INSTITUTE OF NAVAL FORCES OF UKRAINE

National University “Odesa Maritime Academy”

Department “Ship navigation and navigational armament”

Viktor Stepanenko, Maksim Kiriakidi,
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ELECTRICAL-NAVIGATION DEVICES

Study guide

For the students of the Naval institutions for high education

Odesa
“Ecologiya”
2024

UDC 629.5.052(075.8)
S 83

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Reviewed and approved by the department “Ship navigation and navigational armament” as a tutorial for the discipline "Electrical-navigation devices" for the specialty: 255 Armament and military equipment, June 30, 2023, protocol No.9/2023.

Recommended by the Academic Council of the Institute of Naval Forces NU ”OMA” as a study guide for the discipline "Electrical-navigation devices" for the specialty 255 Armaments and military equipment (fields of knowledge 25 Military sciences, national security, security of the state border) (*Protocol No.9/2023 dated 30 June 2023*).

Stepanenko V.V.
S 83 Electrical-navigation devices : study guide for the students of the Naval institutions for high education / Stepanenko V.V., Kiriakidi M.V., Koroshchenko M. M., Chapchay P.O. – Odesa : Ecologiya, 2024. – 120 p.
ISBN 978–617–7867–83–7

The principles of operation, construction and navigational use of modern ship's gyrocompasses, magnetic compasses, speed logs, echo sounders and autopilots are considered. The emphasis is made on the physical phenomena on which the operation of the devices is based.

The study guide is intended for students of the first level of higher education (bachelor) of the Naval Institute of NU ”OMA”, who are studying in the specialty 255 “Armament and military equipment” (field of knowledge 25 “Military sciences, national security, security of the state border”).

UDC 629.5.052(075.8)

ISBN 978–617–7867–83–7

МІНІСТЕРСТВО ОБОРОНИ УКРАЇНИ

ІНСТИТУТ ВІЙСЬКОВО МОРСЬКИХ СИЛ УКРАЇНИ

Національний університет «Одеська морська академія»

Кафедра кораблеводіння та штурманського озброєння

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ЕЛЕКТРОНАВІГАЦІЙНІ ПРИЛАДИ

Навчальний посібник

Для курсантів вищих військових
морських навчальних закладів

УДК 629.5.052(075.8)

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Рекомендовано вченою радою Інституту Військово-Морських Сил НУ «ОМА» як навчальний посібник з дисципліни «Електронавігаційні прилади» для спеціальності 255 Озброєння та військова техніка (галузь знань 25 Воєнні науки, національна безпека, безпека державного кордону) (*Протокол № 9 від 30 червня 2023 р.*)

Розглянуто та схвалено кафедрою Кораблеводіння та штурманського озброєння як навчальний посібник з дисципліни «Електронавігаційні прилади» для спеціальності: 255 Озброєння та військова техніка, 30 червня 2023 р., протокол № 9/2023.

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INTRODUCTION

For the safe management of the vessel, the navigator must be provided with information about the main parameters of its movement and the surrounding navigational dangers. An important part of this information is provided by electrical navigational devices, which include gyroscopic and magnetic compasses, as well as speed logs, echo sounders and autopilots.

The gyrocompass occupies a special place among electrical navigational instruments, since it determines the most important parameter - the vessel's heading. On a moving ship, the gyrocompass has a several errors, which values depends on the mode of ship movement. A navigator must clearly understand the nature of these errors and know how to take them into account and corrected. This study guide discusses the principles of operation and features of the use of two main types of modern gyrocompasses: pendulum ones and with indirect control.

Magnetic compasses are currently used on ships as a mandatory backup heading indicator. A feature of modern magnetic compasses is the presence of special devices to compensate for the deviation caused by the influence of ship's iron.

The study guide describes in detail the types of magnetic compasses deviation and how to compensate for it, which every navigator should know.

The speed of the ship, like the ship's heading, is the important parameter of the ship's movement. Instruments used to measure the ship's speed are speed logs. It can use different principles of functioning; the main ones are described in this study guide.

Currently, hydroacoustic speed logs are most widely used. These devices can measure the speed of a vessel both relative to water and to the ground. Hydroacoustic speed logs are divided into Doppler and correlation types. The principles of operation and the main technical characteristics of these speed logs are discussed in this guide.

Under-keel depth measurements use the same ultrasonic method that has been used for many decades. However, modern navigational echo sounders typically use two different frequencies to measure shallow and deep depths. To display the depth in modern echo sounders, color liquid crystal displays are used, which significantly improve the perception of information

Autopilots are used to automatically keep the vessel's heading. However, modern autopilots differ significantly from their predecessors in the ability to work in an adaptive mode. In this mode, the device automatically selects the optimal route, taking into account the ship's load and the impact of the external environment.

1. BASIC CONCEPTS AND DEFINITIONS

1.1. Navigation definitions

Ship's heading and bearing to reference point are basic concepts of marine navigation.

Heading is the angle in the horizontal plane between the northern part of the meridian and the fore-and-aft line of the vessel.

Bearing is the angle in the horizontal plane between the northern part of the meridian and the direction to the reference point.

As we can see, the meridian is the reference line from which both the ship's heading and bearing are measured. With a known position of the meridian, the determination of the heading and bearing consists in measuring the corresponding angles from the meridian to the fore-and-aft line of the vessel or to the direction of the reference point. Measuring of these angles is done with help of a round card, which is split into 360 degrees and is named ***a dial card***.

All seagoing vessels have devices called ***heading indicators***. For hundreds of years, magnetic compass has only been used as a heading indicator. The needle of magnetic compass finds the meridian and keeps its direction with some accuracy. However, the magnetic meridians do not coincide with the true ones, which are depicted on nautical charts.

The angle between true and magnetic meridians is called ***a magnetic variation***, which is various at different points on the earth's surface. At some places it can reach 10 degrees or more and must be taken into account for navigation. In addition to variation, magnetic compass readings are distorted by the influence of the ship's iron. This error is called ***a magnetic deviation***. The need to account for variation and deviation makes difficult to use a magnetic compass as a heading indicator.

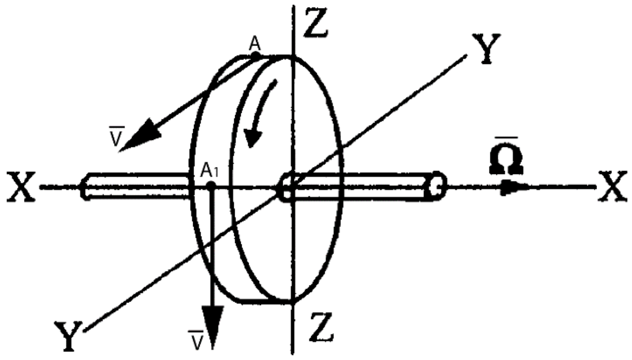
At the beginning of the 20th century, a gyroscopic compass was created. The operating principle of this compass is based on using the properties of a gyroscope and Earth rotation. Gyroscopic heading indicators are much more accurate than magnetic compasses and are not influenced by the ship's iron. Currently, gyrocompasses are mandatory devices for most seagoing vessels. Magnetic compasses are also mandatory for ships due to their simplicity of design and independence from electrical power supply.

For several decades, gyrocompasses used gyroscopes driven into rapid spinning by electric motors. However, it gradually became clear that gyroscopic properties can be exhibited by other devices that do not use a rotor fast spinning. On the basis of these devices, heading indicators have been created, which in a number of parameters are superior to electromechanical gyrocompasses. However, traditional gyrocompasses are widely used on modern ships due to acceptable accuracy and well-developed design.

1.2. Basics of mechanics

1.2.1. Linear and angular velocities

Linear and angular velocities are the basic characteristics of a spinning body. Both of these quantities are vectors. The position of these vectors in relation to a spinning rotor is shown in Fig. 1.1.



$\bar{V}$ – linear velocity vector
$\bar{\Omega}$ - angular velocity vector

$$\bar{V} = \bar{\Omega} \times r$$

Fig. 1.1 – Linear and angular velocities

When the rotor spines, all its points move along circular paths. Each point in one revolution travels a distance S equal to the length of a circle of the corresponding radius R

$$S = 2\pi \times R \qquad 1.1$$

The linear velocity is equal to the distance traveled in a unit of time. The farther a point is from the axis of rotation, the greater the distance it travels in one revolution and the higher its linear velocity. If the speed of rotation is constant, and the time during which one revolution is completed is equal to t_o, then the linear velocity of the point is:

$$\bar{V} = \frac{S}{t_0} = \frac{2\pi R}{t_0} \qquad 1.2$$

The vector of linear velocity of the point is directed tangentially to the trajectory of its movement in the direction of the rotor spinning, as shown in Fig. 1.1.

Note that points of the same rotor located at different distances from the axis of spinning have different linear velocities, and the velocity vector of the same point continuously changes its direction.

The angular velocity is important characteristic of the spinning motion. It characterizes the rotation of the body as a whole. Its direction and values are equal for all points of the rotor. Angular velocity is a vector quantity.

The vector of the angular velocity of a spinning body is situated along the axis of rotation and directed to the side from which the spinning seems to occur counter-clockwise.

The direction of the angular velocity vector can also be determined by the right-hand rule, which is explained in Fig. 1.2.

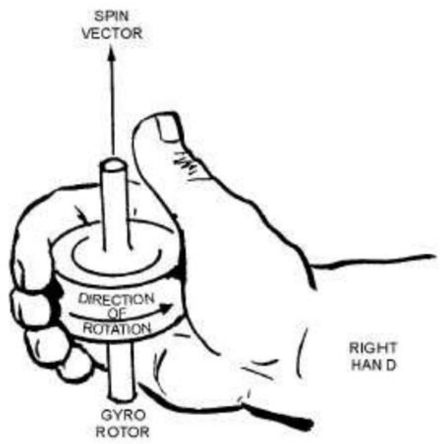


Fig. 1.2 Right hand rule

The Right hand rule

If you position your right hand so that four fingers cover the spinning body, coinciding with the direction of rotation, then the bent thumb will show the direction of the angular velocity vector***:***

Numerically the angular velocity is equal to the angle by which the rotor turns per a unit of time. It is denoted by a Greek letter Ω or ω.

In SI, the unit for angles is radian and the unit for time is second. If we choose the right units of measurement and take into account that the radian is a dimensionless quantity, we get:

$$[\Omega] = \frac{\text{radian}}{\text{second}} = \frac{1}{s} = \text{s}^{-1}$$

Consider the relationship between angular and linear velocities for the case of ***uniform rotary motion***:

In one revolution, all points of the rotor are turned by an angle equal to 2π radians. The time of one revolution is denoted, as before, t_0 seconds

The angular velocity, by definition, is equal to:

$$\Omega = \frac{2\pi}{t_0} \qquad 1.3$$

If we substitute expression 1.3 into formula 1.2, we get:

$$\bar{V} = \bar{\Omega} \times R \qquad 1.4$$

This expression shows the relationship between angular and linear velocities of a uniformly spinning disk. It will be used in the future explanations.

In the particular case when the radius of the disk is 1 m, the angular and linear velocities are numerically equal.

In more complex cases, when the main axis of the rotor changes its position in space, the angular velocity vector changes its direction along with it. To determine the position of the rotor's angular velocity vector, it is convenient to use the linear velocity vector of its end point. Mathematical analysis proves that the time derivative of the angular velocity vector is equal to the linear velocity of the end of this vector, that is:

$$\frac{d\bar{\Omega}}{dt} = \bar{v} \qquad 1.5$$

The linear velocity $\bar{v}$ of the end of the vector $\bar{\Omega}$ should not be confused with the linear speeds of the points of the rotating rotor.

1.2.2 Torque

If the force acts on the body in such a way that tends to turn it around some axis, then it creates a torque about this axis. The torque is a vector quantity.

The direction of the torque vector is determined by the right screw rule.

It should be emphasized that the torque vector is directed perpendicular to the plane of action of the force. Torque vector direction is shown in Fig. 1.3.

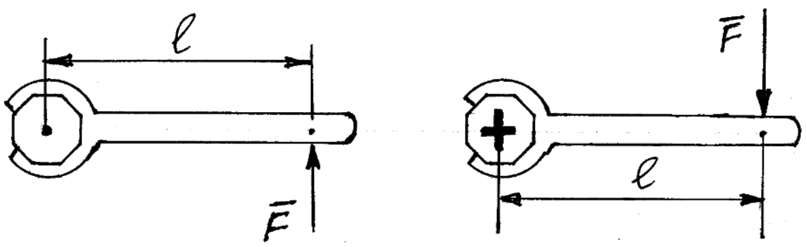


Fig. 1.3 Torque vector direction

Numerically, the torque magnitude is equal to the product of the force by the distance from the axis to the point of the force application. This distance is called the arm of the force.

$$\bar{\boldsymbol{L}} = \bar{\boldsymbol{F}} \times \boldsymbol{l}$$

2. THE GYROSCOPE AND ITS PROPERTIES

To understand the operation of a gyrocompass, we must first study the gyroscope design and its properties. It is convenient to do this using the example of a traditional mechanical gyroscope.

2.1. Definition of term “gyroscope”

In the technique a gyroscope is traditionally understood as a dynamically symmetric rapidly spinning rigid body, which axis of rotation can arbitrarily change its direction in space.

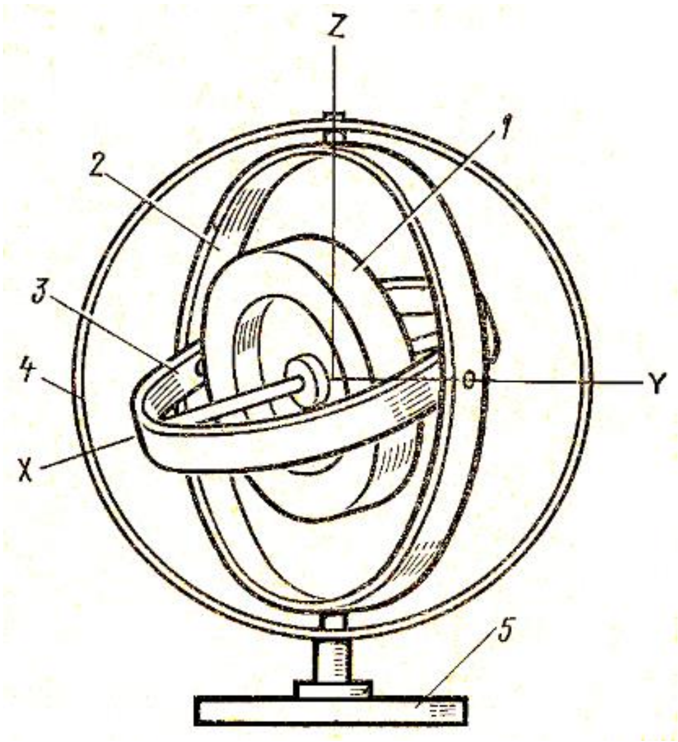


Fig. 2.1. Laboratoty gyroscope

The laboratory model of the gyroscope is shown in Fig. 2.1.

1 - Rotor
2 – Vertical ring
3 – Inner ring
4 – Outer ring
5 – Base

The rotor is rigidly mounted on the axle that enters bearings fixed on opposite sides of the inner ring. This axis is called the “spinning” or “main” axis and is designated by the letters X.

The inner ring, together with the rotor, can turn inside the vertical ring around the Y axis, perpendicular to the X axis. Finally, the vertical ring can rotate inside the outer ring around the vertical Z axis.

All three axes of the gyroscope are mutually perpendicular and intersect at an imaginary point called the ***center of suspension***. The center of suspension does not change its position at any position of the main axis of the gyroscope.

The considered gyroscope can rotate around three axes, that is why it is called a gyroscope with ***three degrees of freedom***.

If the gyroscope is deprived of the ability to rotate around one of the axes – Y-Y or Z-Z, it becomes a gyroscope with two degrees of freedom.

A gyroscope that can only rotate around the spinning (main) axis is called a gyroscope with one degree of freedom.

Definition*:* a gyroscope with three degrees of freedom whose center of gravity coincides with the center of the suspension is called a ***balanced gyroscope***.

The immovable rotor of a balanced gyroscope is in a state of indifferent equilibrium at any position of its main axis, since the gravity of the gyroscope is balanced by the reaction of the support.

Definition: A balanced gyroscope that is not affected by any external forces is called a free gyroscope.

The free gyroscope has three remarkable properties due to which it is used as the main component of a gyro compass.

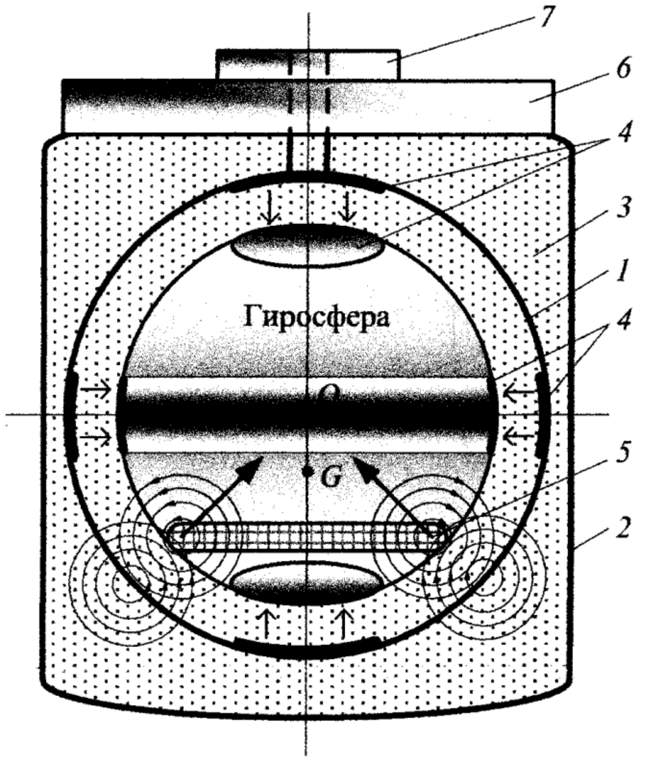
2.2. Suspension of gyroscopes

The mechanical suspension of the gyroscope shown on the Fig. 2.1 is classical. It is called “Cardano gimbal” after the Italian scientist Cardano who created it first. In modern gyrocompasses, other methods are used, which is discussed below.

The Fig. 2.2 shows the hydrostatic suspension of the gyrosphere in combination with the electromagnetic one, which is used in the double-gyro pendulum gyrocompasses of the "Курс" type and others.

A gyrosphere (sensitive element) with two gyroscopes is placed inside a tracking sphere ***1***, which, in turn, is located in a reservoir ***2*** filled with a supporting fluid ***3***. The supporting fluid is conductive and provides power supply to the gyroscopes through electrodes ***4*** located on the surface of the gyrosphere and the tracking sphere. Three-phase asynchronous electric motors are used as gyroscopes. The rotation speed of the motors is approximately equal to 20,000 revolutions per minute (RPM).

In lower part of the gyrosphere there is a horizontal toroidal winding ***5*** through which an alternating current flows. The magnetic field of the winding induces eddy currents in the outer tracking sphere. As a result, forces arise that compensate for the negative buoyancy of the gyrosphere and prevent it from touching the tracking sphere when the ship is maneuvering or rolling.



SE – Sensitive element
1 - Tracking sphere
2 - Reservoir
3 - Supporting fluid
4 - Electrodes
5 - Toroidal coil
6 - Reservoir lid (table)
7 - Heading indicator

Fig. 2.2. Liquid suspension of a sensitive element

At a constant temperature of the supporting fluid and in the absence of external influences, the gyrosphere retains its position unchanged. Changes in the course of the vessel are synchronously processed (tracked) by the tracking sphere, which through table 6 has a connection with the heading indicator 7. On the table there are elements of power supply, control, correction, etc.

Such a sensitive element was first created in 1927 in Germany by the company Anschütz. Some modern gyrocompasses from Anschütz use a hydrodynamic method for centering the gyrosphere, which is implemented using a miniature pump.

2.3. Angular momentum

The higher the spinning velocity of the rotor and its mass are, the more pronounced its gyroscopic properties. The distribution of mass over the rotor area is also important. The main parameter of the gyroscope is angular momentum. It is a generalized characteristic of a gyroscope since it takes into account all factors on which gyroscopic properties depends on.

Let us consider this issue in more detail using Fig. 2.3

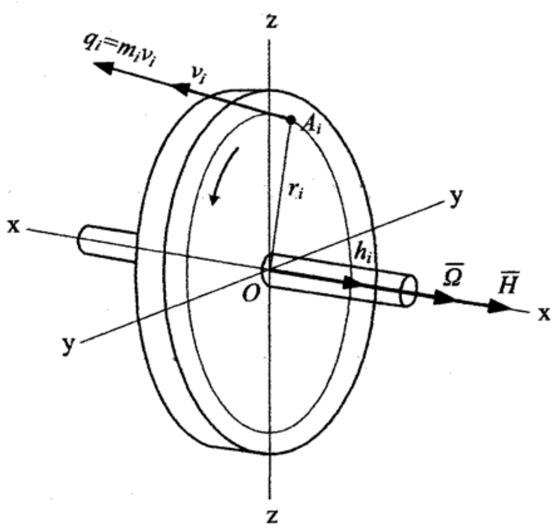


Fig. 2.3. The angular momentum

The rotor is made up of countless particles. Each particle has an elementary momentum q_i which is equal to:

$$q_i = m_i \times v_i$$

Angular momentum of the elementary particle is equal to the product of its momentum by the radius:

$$h_i = q_i \times r_i = m_i \times v_i \times r_i$$

Taking into account that: $v_i = \Omega \times r_i$ we get:

$$h_i = \Omega \times m_i \times r_i^2$$

The total angular momentum of entire rotor is equal:

$$\bar{H} = \bar{\Omega} \sum_{i=1}^{n} m_i r_i^2$$

The sum $\sum_{i=1}^{n} m_i r_i^2$ = J is named ***moment of inertia***

So as a result we have:

$$\bar{H} = \bar{\Omega} \times J$$

The vector of angular momentum $\bar{H}$ coincides in direction with the vector of angular velocity $\bar{\Omega}$. It is plotted on the main axis of the gyroscope according to the same rules.

2.4. Properties of free gyroscope

As was pointed above a ***balanced gyroscope*** that is not affected by any external forces is called **a *free gyroscope*.**

A free gyroscope has three remarkable properties, which are as follows

1. Gyroscopic inertia

2. Precession (not confuse with precision)

3. Impact resistance

Gyroscopic inertia is the free gyroscope property by which its main axis keeps unchanged its direction in inertial space for any movement of the gyroscope base.

In other words, the main axis of a free gyroscope remains its direction unchanged relatively to the stars, but moves relatively to the Earth's objects. Such a movement is called "apparent". This property permits observer to determine the Earth's rotation.

To understand apparent movement of the free gyroscope we should remember that for observer in northern hemisphere, the sky rotates counterclockwise around the Polar Star.

The second property of the gyroscope (precession) is that under the external force which torque does not coincide with the direction of the main axis, the latter will turn in a plane perpendicular to the direction of the applied force.

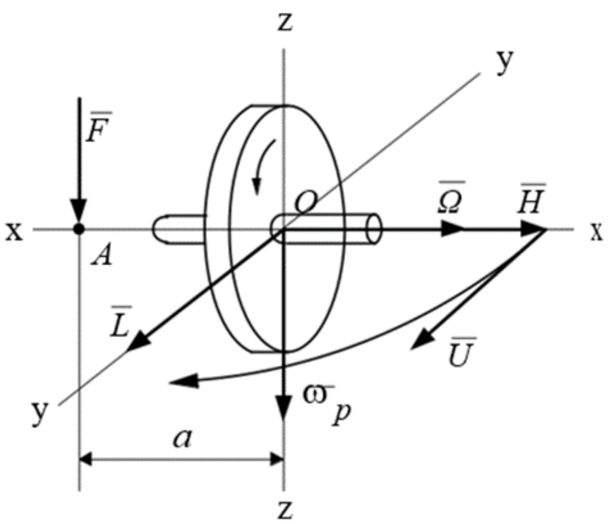


Fig. 2.4. Precession of the gyroscope

The direction of the precession motion is determined as follows:

In the precession motion, the vector of the angular momentum $\overline{H}$ tends to the vector of the external torque $\overline{L}$ along the shortest path.

In case of the torque vector direction coincide with the angular momentum vector precession doesn't arise

The third property of the gyroscope - impact resistance is as follows:

Under the action of an impulse of force (impact), the main axis of the gyroscope does not change its direction. There are only arises fast damped oscillations of the main axis, which are called "nutation.".

2.5. Horizontal coordinate system and its rotation

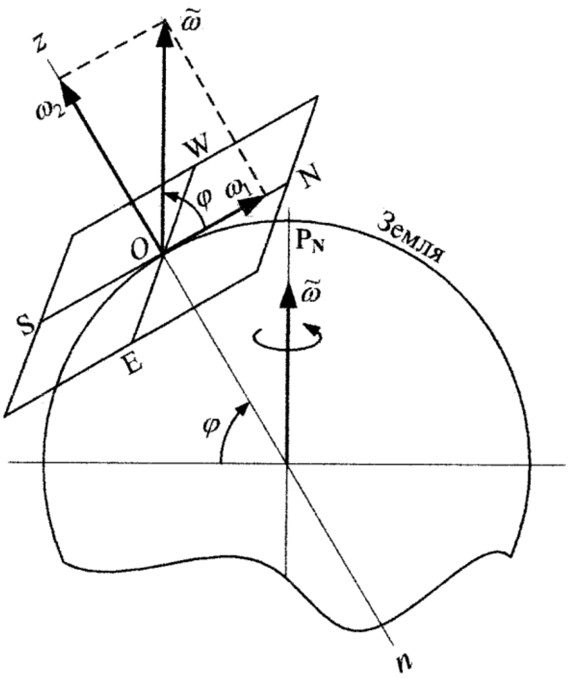


Fig 2.5. Horizontal coordinate system

With the help of a free gyroscope, it is possible to trace the daily rotation of the Earth around its axis.

Since the GS retains its original position, and the Earth rotates with the observer, the observer sees that the GS rotates relative to the planes of the true meridian and the true horizon, which are associated with the observer's point on the Earth's surface.

Figure 2.5 shows a spherical model of the Earth and a horizontal coordinate system NEn associated with some point O on the Earth's surface.

The NS axis is directed tangentially to the meridian to the north; EW axis - tangentially to the parallel to the east; On axis - along the plumb line to the nadir.

Due to the daily rotation of the Earth with an angular velocity $\tilde{\omega}$, the horizontal coordinate system ONEn will also rotate.

Let us decompose the $\tilde{\omega}$ vector into its components; ω_1 along the noon line NS; ω_2 - along the plumb line Zn. The vectors $\tilde{\omega}$, ω_1, ω_2 are in the plane of the true meridian.

For the values of the angular velocities ω_1 and ω_2, we have the relation

$\overline{\omega}_1 = \tilde{\omega}\, cos\varphi$ – horizontal component of the Earth rotation;

$\overline{\omega_2} = \tilde{\omega}\, sin\varphi$ – vertical component of the Earth rotation

where φ is the observer's latitude.

The horizontal component of the Earth's diurnal rotation shows that the plane of the observer's true horizon continuously rotates in space around the midday line NS so that the eastern half of the horizon goes down and the western half rises (from the end of the vector ω_1 this rotation is observed counterclockwise).

The vertical component of the Earth's diurnal rotation shows that for an observer located in the northern hemisphere, the plane of the true meridian rotates in space around the plumb line Zn so that the northern part of the meridian plane continuously departs to the west, and the southern part to the east (from the end of the vector ω_2 this rotation is observed counterclockwise). In the southern hemisphere - the rotation is reversed.

2.6. Free gyroscope apparent movement

Let us consider several cases of the apparent motion of a free gyroscope installed at various points on the earth's surface shown in the Fig. 2.6.

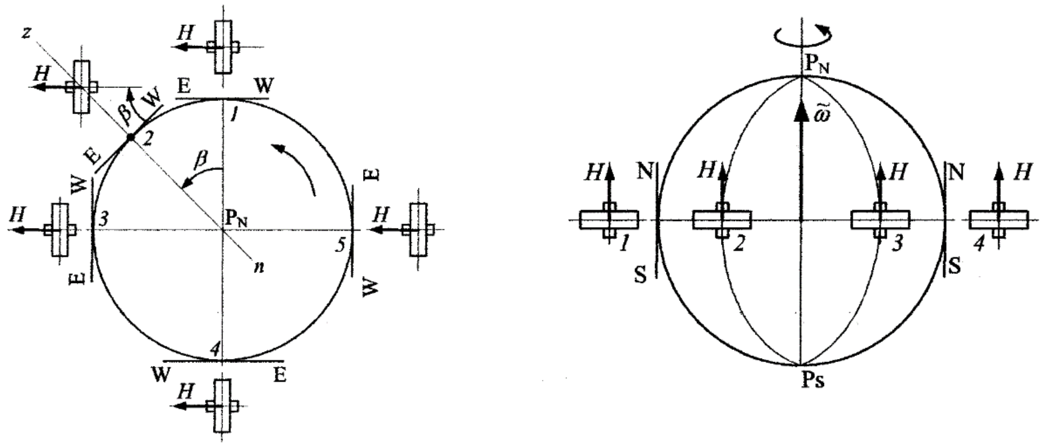


Fig. 2.6. Apparent movement of a free gyroscope on equator

1.The gyroscope is located at the equator, its X – X axis is horizontal and directed along the EW line. After a certain period of time, the Earth will turn through an angle β. The axis of the gyroscope remains unchanged in its position in space (the first property of the gyroscope). The observer will mark the rise of the gyroscope axis by the same angle β. During the day, after passing the time stages 1 - 5, the axis of the GS makes a full revolution in the vertical plane.

2. The gyroscope is at the equator, its X – X axis is horizontal and directed along the NS line. Since the GS axis is parallel to the Earth's rotation axis, the observer will not detect the visible movement of the gyroscope.

3. The gyroscope is located in the middle northern latitude, originally in the plane of meridian and its axis is horizontal. At the very next moment the X-X axis of the device will deviate from the observer's meridian by an angle $\boldsymbol{\alpha}$ (due to the presence of ω_2).

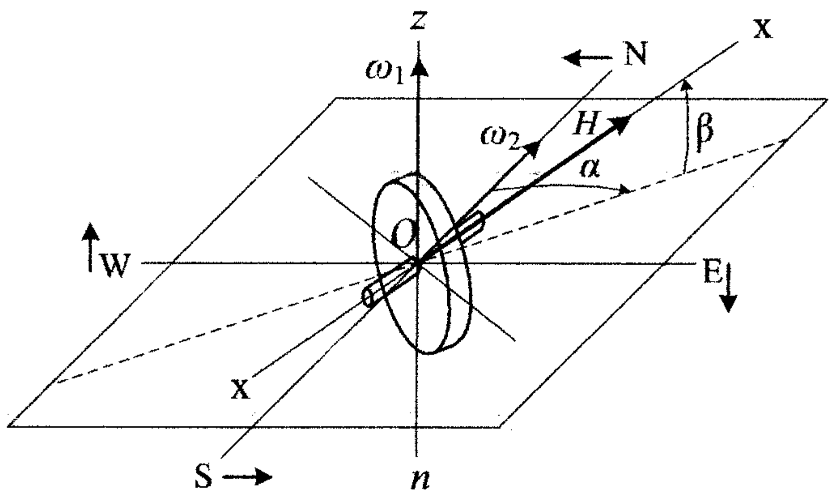


Fig. 2.7. Free GS main axis apparent movement in the North latitude

Simultaneously with the visible departure from the meridian, the eastern end of the main axis will rise above the horizon plane by an angle $\boldsymbol{\beta}$ above the horizon since the latter rotates with the Earth, and its eastern half continuously descends (presence of ω_1). So it becomes obvious that:

A free gyroscope cannot be used as a heading indicator, because its main axis continuously moves away from the meridian and at the same time deviates from the horizon plane.

3. GYROCOMPASSES WITH AUTONOMOUS SENSITIVE ELEMENT

3.1. Turning a gyroscope into a sensitive element of a gyrocompass

3.1.1. Lowering the gyroscope center of gravity

The Fig. 3.1 shows a gyroscope (GS) enclosed into a gyro chamber, in the lower part of which a weight is fixed, due to which the center of gravity (CG) of the gyro chamber is displaced downward relative to the suspension point O by a distance called a metacentric height **(a)** of the sensitive element (SE).

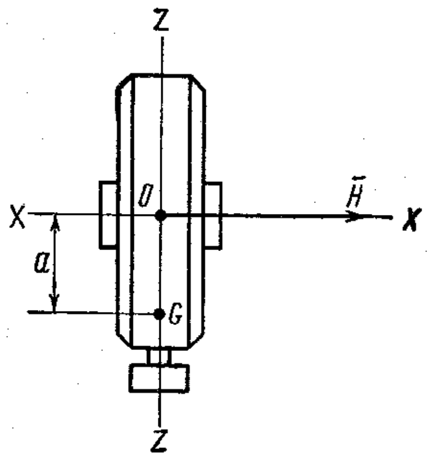


Fig. 3.1. GS with a lowered center of gravity

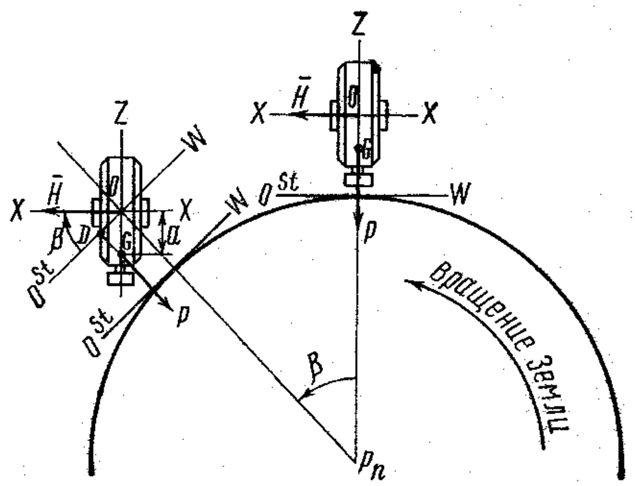


Fig. 3.2. Movement of the sensitive element with lowered CG

Gyroscope with a lowered center of gravity retains the properties of a gyroscope and additionally acquires the properties of a pendulum. As we know the property of a pendulum is that it tends to occupy such a position in space so that its center of gravity is located on a plumb line. The device shown in the Fig. 3.1 combines the properties of a gyroscope and a pendulum. Such a device is also known as a “gyroscope with rigid pendulum”.

Let us consider that a gyroscope with a lowered center of gravity is positioned at the equator in such a way that initially its main axis is horizontal and the angular momentum vector $\overline{H}$ is directed to the East as shown in Fig. 3.2.

Due to a property of gyroscopic inertia, the rotation of the Earth induces a continuous change of the gyroscope position relative to the plumb line. For clarity, Fig. 3.2 shows the second position of the gyroscope after about three hours later the initial one, when the Earth turned through an angle $\boldsymbol{\beta}$ equal to approximately 45 degrees. The gyroscope center of gravity is deflected from the plumb line by the same angle $\boldsymbol{\beta}$, so a gravity torque arises that causes to return the center of gravity to the plumb line.

The gravity torque vector is located along the Y-Y axis of the gyroscope and is directed towards the observer, i.e. to the north. Under the action of the gravity torque, the precession motion of the gyroscope arises. In accordance with the rule of precession direction that we studied earlier, the angular momentum vector $\overline{\boldsymbol{H}}$ of the gyroscope tends to the gravity torque vector $\overline{\boldsymbol{L}}$ along the shortest path.

Since the angular momentum vector of the gyroscope coincides with its main axis, the gyroscope will turn to the north i.e. to the meridian. The angular velocity vector $\overline{\boldsymbol{\omega}}$ of the precessional motion of the gyroscope is located along the plumb line and directed to Zenith. Let's calculate its value as follows:

Designate the mass of the sensing element (SE) with the letter $\boldsymbol{m}$

Then the force of gravity $\overline{\boldsymbol{P}}$ acting on the SE is equal to:

$$\overline{\boldsymbol{P}} = \boldsymbol{m} \cdot \boldsymbol{g}$$

Pendulum torque is equal to the product of force per the force arm:

$$\overline{\boldsymbol{L}} = \overline{\boldsymbol{P}} \cdot \boldsymbol{l} = \boldsymbol{mg \cdot a \cdot sin\beta}; \qquad 3.1$$

where $\boldsymbol{l}$ is determined from triangle ODG and is equal to:

$$\boldsymbol{l} = \boldsymbol{a} \cdot \boldsymbol{sin} \cdot \boldsymbol{\beta}$$

where $\boldsymbol{a}$ is the metacentric height (hypotenuse OG in the triangle ODG)

Let's introduce the notation:

$\boldsymbol{B = mga}$ – module of the pendulum torque.

Taking in account that for small angles $\boldsymbol{sin\beta} = \boldsymbol{\beta}$, we have:

$$\overline{\boldsymbol{L}} = \boldsymbol{B} \cdot \boldsymbol{\beta} \qquad 3.2$$

The angular velocity of the SE precession to the meridian is:

$$\omega_p = \frac{\overline{L}}{\overline{H}} = \frac{B\beta}{H} \qquad 3.3.$$

Thus, the gyroscope becomes an indicator of the meridian, i.e. sensitive element of the gyrocompass.

It should be noted that for all gyrocompasses with lowered center of gravity, the angular momentum vector of the gyroscope points to the north, as it is shown in the Fig. 3.2.

Due to Earth rotation the main axis of a gyroscope with a lowered center of gravity moves to the meridian so that its angular momentum vector points to the North. Therefore, such a gyroscope can be used as a sensitive element of a gyrocompass.

This method also known as “a rigid pendulum method” has been developed by the German inventor Anschütz. He founded a company that is now well known over the world. The company has developed many models of gyrocompasses, which use the rigid pendulum method. All models of the "Standard" brand (14, 20, 22) belong to these gyrocompasses. The same method is used in gyrocompasses «Курс» type that are studied in the laboratory.

3.1.2. Attachment of vessels with mercury to the gyro chamber

Figure 3.3 shows a gyro chamber to which two communicating vessels with a heavy liquid (mercury) are attached. The vessels are located symmetrically on both sides of the gyro chamber so that the horizontal axis X-X of the gyroscope is perpendicular to the vessels. When the gyro chamber turns, the vessels turn with it.

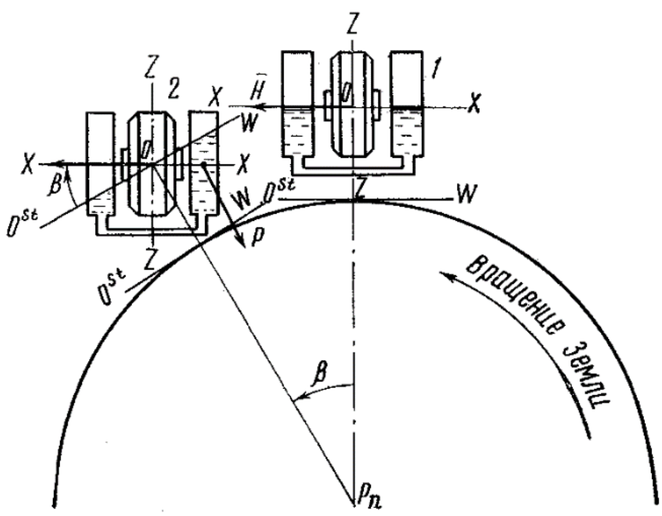


Fig 3.3. Movement of the SE with the mercury vessels

The entire device is balanced so that in horizontal position its center of gravity coincides with the center of suspension.

Suppose that at the initial moment (position 1) the main X-X axis of the device is horizontal and directed along the E-W line. In this position both vessels have equal quantity of mercury and no external torques apply to the gyroscope.

The next moment in time, as a result of the Earth's rotation, the main axis X-X of the device will be inclined to the horizon plane at an angle $\boldsymbol{\beta}$ (position 2). At the same time, the vessels rigidly connected to the gyro chamber will also tilt at the same angle. Mercury is a liquid therefore it is located in vessels so that its level coincides with the horizon. This is why the mercury will flow into the lowered vessel in which an excess of liquid is formed. The gravity force of the excess liquid in the lowered vessel creates a torque $\bar{L}$ relative to the Y-Y axis, directed behind the plane of drawing (to the South). The torque will cause the precession of the sensitive element around the Z-Z axes in direction to meridian (to the South).

Gyroscope with mercury vessels solves the same problems as the gyroscope with a lowered center of gravity. But in contrast to the latter, the angular momentum vector of a gyroscope with mercury vessels points to the South.

The method of mercury vessels was first applied by the American engineer Sperry. The company he founded successfully operates till the present time. In addition to gyrocompasses the company produces the most modern marine navigation equipment. One can find the equipment produced by “Sperry marine” company on almost all modern vessels.

Summary: We have studied two ways to make the gyroscope sensitive to the direction of the meridian and move in that direction. Gyrocompasses in which one of these methods is used are called “pendulum” or “direct-controlled gyrocompasses.” There are other ways to convert a gyroscope into a gyrocompass, but these two are classical. Today they are widely applied in the marine gyrocompasses.

3.2. Continuous oscillation of the gyrocompass sensitive element

We have studied two methods that make the gyroscope sensitive relative to the meridian and provide movement of the main axis to it. However, we have not considered in detail how this movement occurs.

Let us consider in more detail the movement of main axis of the SE with lowered center of gravity, installed at a certain northern latitude φ.

The figure 3.4 shows the trajectory of the main axis of the sensitive element on the plane Q located in front of the sensitive element perpendicular to the planes of horizon and the meridian. The line MM is a trace from the intersection of the observer’s meridian plane with the plane Q, and the line WE is the trace of intersection of the plane Q with the plane of the horizon.

Let at the initial moment the axis of the device is horizontal and deviated from the meridian by some small angle α to the east. The projection of the end of the vector H onto the vertical plane Q, gives point 1, as it shown in Fig. 3.4. Each next point of the projection is determined by the resultant of the following linear velocities:

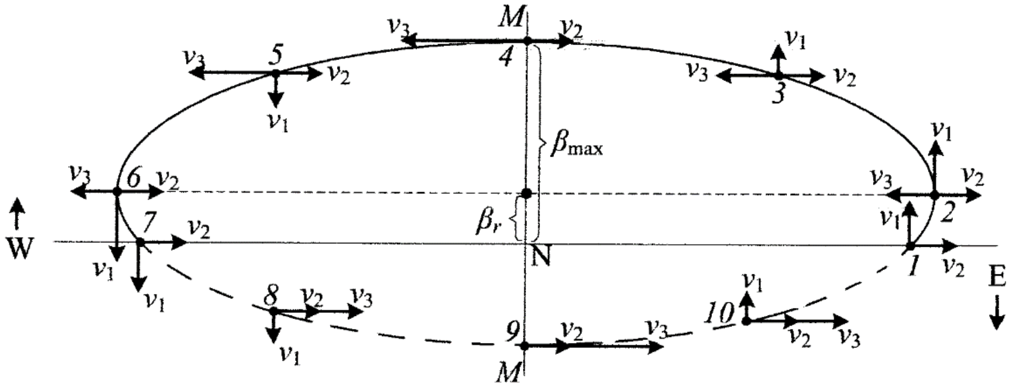


Fig. 3.4. Continuous oscillations of the sensitive element

v₁ = *f* (α) - shows the rise (lowering) of the main axis of the gyroscope relative to the horizon plane, which continuously rotates about the NS line with an angular velocity $\boldsymbol{\omega_1}$ (see section 2.5);

When the gyroscope main axis is in the eastern part of the horizon, its visible rise occurs, and, being in the western part of the horizon, the axis is lowered.

$\boldsymbol{v_2}$ = const in all cases for a given latitude, since the plane of the true meridian rotates around the plumb line Zn with an angular velocity ω_2 (see item 1.5);

$\boldsymbol{v_3}$ = *f* (β) is due to the gyroscope precession, which is created by the pendulum torque of the gyroscope. This velocity is different at different points of the trajectory. Precession obeys the following rule: in precession motion the gyroscope angular momentum vector tends to the external torque vector along the shortest path. In our case, the external torque is the pendulum torque. To understand the direction of the pendulum torque vector, consider Fig. 3.5.

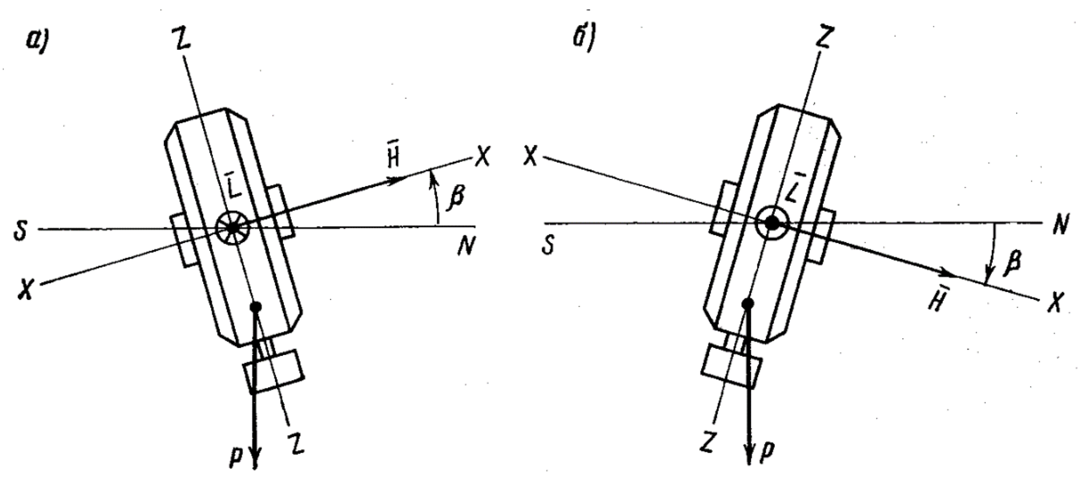


Fig. 3.5. The pendulum torque vector direction

Under the action of the of gravity torque, the gyroscope is tilted around the Y-Y axis, which runs perpendicular to the plane of the figure. The direction of the pendulum torque vector is determined by the right screw rule and is as follows:

Fig. “a”: (main axis is raised above the horizon) - the vector passes perpendicular to the plane of the drawing FROM the observer (to the West);

Fig. “b”: (main axis is lowered below the horizon) - the vector passes perpendicular to the plane of the drawing TO the observer (to the East).

If the main axis of the gyroscope is horizontal, there is no moment of force, since the center of gravity of the gyroscope is located on the plumb line.

Thus, a GS with a lowered center of mass, being taken out of the meridian, performs continuous oscillations around it, and with good reason we can call it a sensitive element of the gyrocompass.

Position of the dynamic equilibrium of the main axis of the SE.

Due to the existing frictional forces in the suspension, in fact, the oscillations do not take place along an elliptical trajectory, but along an extremely slowly converging spiral, and therefore they are damping.

The motion of the main axis of the gyroscope with a lowered center of gravity under the action of the Earth's rotation is described by the following system of differential equations

$$\left.\begin{aligned} &H\dot{\alpha} + B\beta = H\tilde{\omega}\sin\varphi\ ; \\ &H\dot{\beta} - H\tilde{\omega}\cos\varphi\,\alpha = 0\ . \end{aligned}\right\} \qquad (3.2)$$

The current position of the main axis of the gyroscope is characterized by the angles of deviation the main axis from the plane of the meridian (angle α) and the plane of the horizon (angle β). The ellipse of continuous oscillations drawn in this coordinate system is shown in Fig. 3.6.

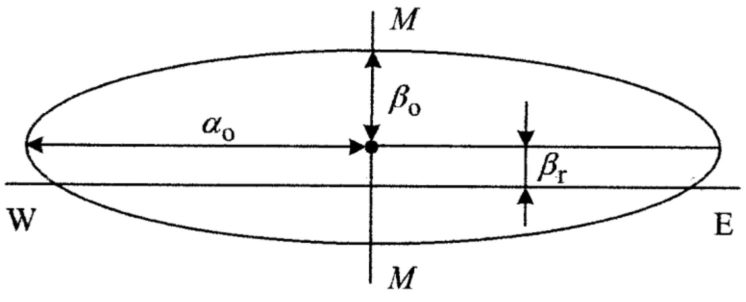


Fig 3.6. Ellipse of the SE continuous oscillation

In addition to the angles $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ and their derivatives $\dot{\boldsymbol{\alpha}}$ and $\dot{\boldsymbol{\beta}}$ the equation 3.2 includes the following quantities:

H – gyroscope angular momentum;

B – pendulum torque module;
$\widetilde{\omega}$ – gyroscope angular velocity;
φ – observer's latitude

The theory and practice prove that after a long period of oscillation, the main axis eventually stops in a position that is called a dynamic equilibrium point.

The solution of equation 3.2 with certain initial conditions gives the coordinates of the point of dynamic equilibrium as follows:

$$\alpha_r = 0, \qquad \beta_r = \frac{H\widetilde{\omega}sin\varphi}{B} ;$$

The results obtained show that the main axis will stop at the meridian ($\alpha_r = 0$), but will be raised above the horizon by an angle β_r. The fact that $\beta_r \neq 0$ has a deep physical meaning. It means that the main axis has a continuous precessional movement (to the west). The speed of this movement is equal to the speed of the meridian due to the vertical component of the earth's rotation.

It follows from the formula that β_r depends on latitude. At the equator $\boldsymbol{sin\varphi = 0}$, so $\boldsymbol{\beta_r = 0}$. With latitude increasing the value of β_r also increases and reaches its maximum at the poles.

The main axis of the gyroscope with lowered center of gravity after continuous oscillation eventually set to the position of dynamic equilibrium which coincide with meridian but deflected from the horizon on the angle β_r. depended on latitude.

The rise of the main axis above the horizon is equal to fractions of a degree. For example, for the "Курс-4" gyrocompass in latitude 60°, the angle β_r= 0.1°.

3.3. Damped oscillations of the gyrocompass sensitive element

The continuous oscillations of the sensing element of the «Курс-4» gyrocompass spontaneously finish after about 2 weeks. All this time the gyrocompass is not ready for use. The same happen if the gyrocompass is started after a stop during the ship is at sea. Such a situation is unacceptable; therefore, measures are taken in gyrocompasses to accelerate the damping its continuous oscillations. For practical use of the gyrocompass, it is necessary to accelerate the process of damping its continuous oscillations without increasing the friction in the suspension. This problem is solved by creating an additional horizontal torque that constantly acts on the sensitive element. When sensitive element (SE) moves away from the meridian, the additional torque hinder that, and when SE moves towards the meridian, the additional torque helps to that. Since the additional torque dampens the natural oscillations of the SE, it is called the damping torque.

The classical way to create such a torque is to use a liquid damper. Schematically, it represents two communicating vessels (Fig. 3.7) fixed in the upper part of the gyrochamber by its north and south sides. The vessels half filled with a viscous liquid, usually vaseline oil.

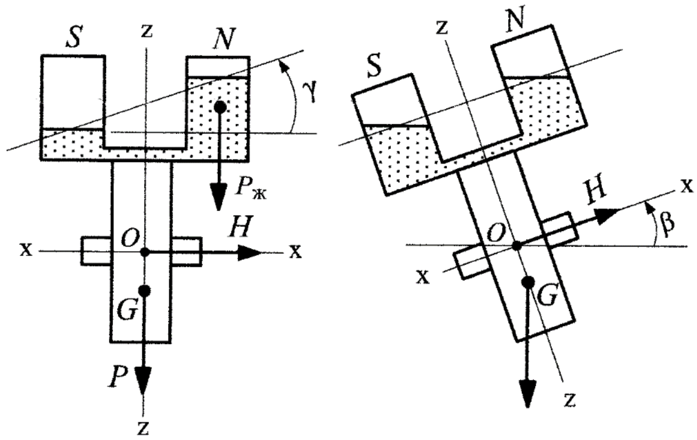


Fig. 3.7. Liquid (oil) damper

Due to SE tilts around the Y-Y horizontal axis, the liquid flows from the raised vessel to the lowered one. The gravity of the liquid excess in one of the vessels creates an additional gravity torque about the Y-Y-axis.

The design of the vessels, the diameter of the connecting tube and the viscosity of the liquid are selected so that the oscillations of the liquid in the vessels lag behind in phase by 1/4 of the period relatively to the natural oscillations of the gyrosphere.

This means that when the gyrosphere is horizontal, the difference in liquid levels in the vessels is maximum, and when the tilt of the gyrosphere is the greatest, the liquids in the vessels are equal.

The process of formation of damped oscillations.

Let at the initial moment position of the main axis of the SE corresponds to fig. 3.4.

Each point of the vector $\overline{H}$ projection trajectory on the vertical plane $\boldsymbol{Q}$ is determined by the summation of linear velocities in the same way as for the continuous oscillations:

$\boldsymbol{v_1} = f(\alpha)$; $\boldsymbol{v_2} = \text{const}$; $\boldsymbol{v_3} = f(\beta)$. Let us trace the main stages of the main axis movement in the presence of an oil damper [2].

1. If the mode of oil oscillations in the vessels has already been stabilized, i.e. the liquid oscillations are delayed in phase by 1/4 of the period relative to the CO period, then the maximum excess of liquid will be in the northern vessel.

The gravity force of the liquid excess $\boldsymbol{P_{LE}}$ creates a torque about the Y–Y axis, the vector of which is directed to the west. This torque will cause precession around the Z-Z axis, and therefore the main axis will begin to move towards W, i.e. to the meridian plane with a linear velocity $\boldsymbol{v_4} = \boldsymbol{f(\gamma)}$, which is the result of the additional precession.

2. When, after 1/4 of the oscillation period, the main axis of the device comes to the meridian (point 3), the angle $\boldsymbol{\beta}$ of the main axis rise above the horizon will be maximum and, consequently, the liquid in the vessels becomes equal and the action of additional torque $\boldsymbol{L_{LE}}$ stops.

3. When the main axis passes to the western part of the horizon, the liquid continues to flow into the southern vessel, forming an increasing excess in it. The torque $\boldsymbol{L_{LE}}$, and, consequently, the linear velocity $\boldsymbol{v_4}$ change their directions to the opposite ones. The linear velocity $\boldsymbol{v_4}$ will again be directed towards the meridian. In the point 6, the axis of the device will become horizontal, the maximum excess of liquid will form in the southern vessel, and $\boldsymbol{v_4}$ will be maximum.

4. After the point 6, the northern end of the SE axis will descend under the horizon and simultaneously move towards the meridian. The liquid will begin to flow from the south vessel to the north one. In point 7, the axis will be set in the meridian, the oil levels in the vessels will be equal, therefore, $\boldsymbol{v_4} = 0$.

In the future, the main axis of the SE, having risen above the horizon, will again get additional movement towards the meridian and will soon reach a position of dynamic equilibrium.

The sensitive element damped oscillations formation is shown in Fig. 3.8.

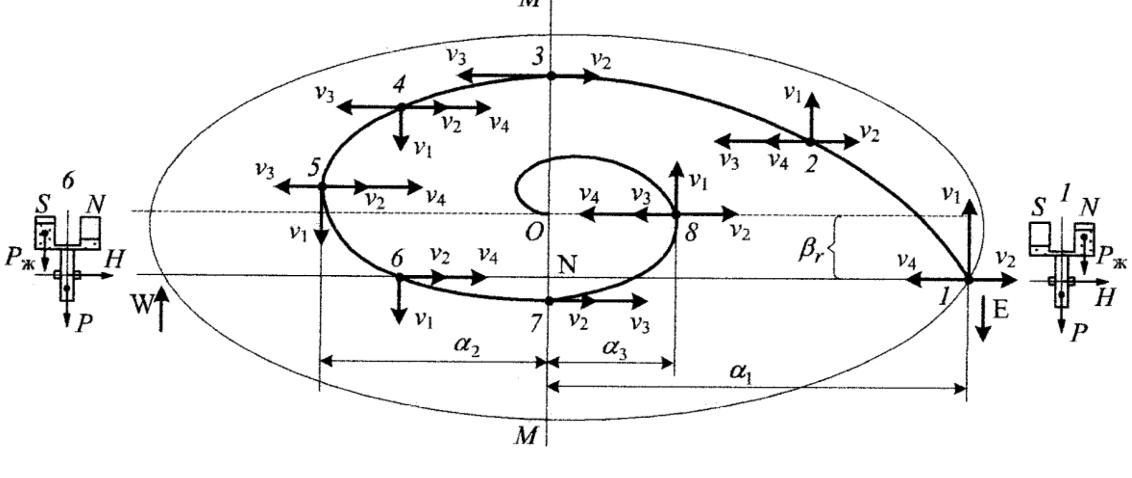


Fig. 3.8. Damped oscillations of the sensitive element

3.4. Speed error of the gyrocompass

The sensitive element of gyrocompass (GC) comes to the meridian and keeps this position due to a constantly acting pendulum torque $\boldsymbol{Ly = B\beta}$, where the angle β of deviation of the main axis X-X from the horizon plane is a consequence of the continuous rotation of this plane. Thus, the physical quantity to which the GC reacts is the horizontal component of the Earth angular velocity directed along NS line:

$$\omega_1 = \tilde{\omega}\cos\varphi.$$

In all the questions considered earlier, it was meant that the gyrocompass is located on a fixed base, but on a moving ship, the operating conditions of the GC become different. In this case, the GC is affected by the ship's own motion, changes of its speed and course, rolling, causing additional deviations of the GC axis from the meridian, i.e. errors in its readings, which under certain conditions can reach significant values.

The error that occurs due to ship’s movement at a constant speed and with a constant course is called speed error.

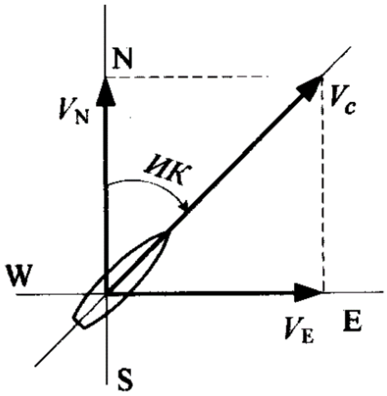


Fig. 3.9. Components of the ship’s speed

Vessel movement with speed V_S and true heading ИК can also be specified in the form of speed components along the meridian and parallel respectively, as it shown in (Fig.3.9):

$$V_N = Vc\ cosИК$$

$$V_E = Vc\ sinИК.$$

Fig. 3.10 shows the horizontal coordinate system ONEn associated with the ship located at point O in latitude $\boldsymbol{\varphi}$.

Linear velocity component $\boldsymbol{V_N}$ is directed along the meridian which is the arc of a great circle with radius $\tilde{\boldsymbol{R}}$. So this movement is circular and is characterised by the angular velocity vector $\boldsymbol{\omega_N}$, which is directed along the line EW to W (from the end of the vector $\boldsymbol{\omega_N}$, the direction of the vector $\boldsymbol{V_N}$ is observed counterclockwise).

Moving along the parallel (along the arc of a small circle with a radius $\boldsymbol{r}$) with a component of the linear velocity $\boldsymbol{V_E}$, the ship makes a circular motion with an angular velocity $\boldsymbol{\omega_E}$.

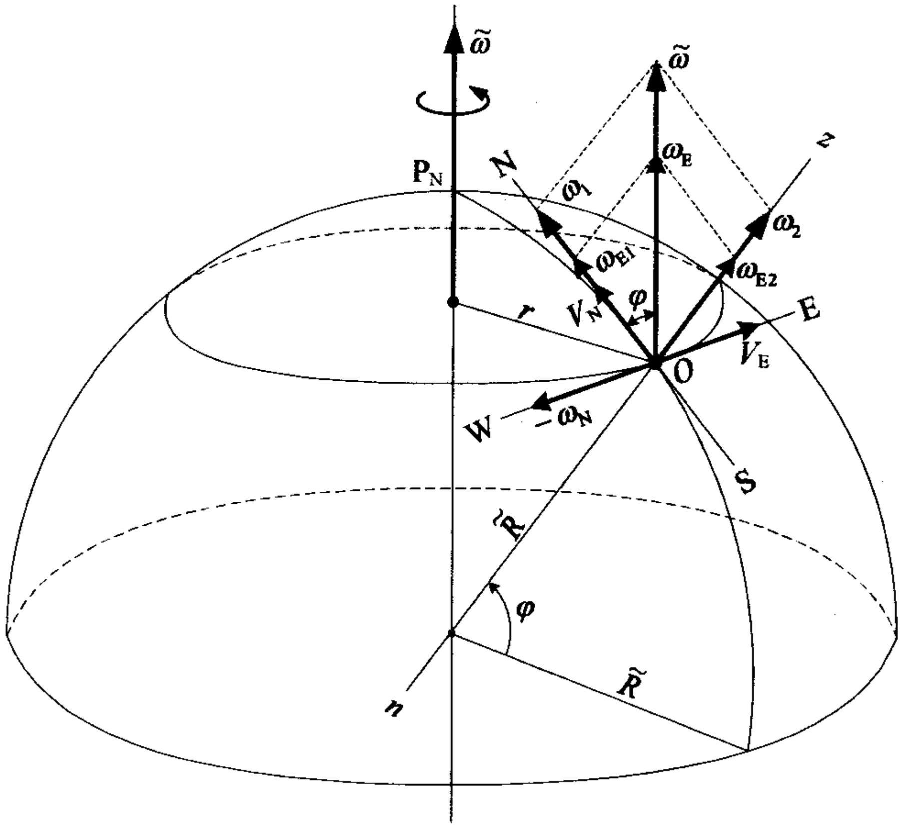


Fig. 3.10. Components of the angular velocities characterizing the ship movement

Using the known relationship, we have:

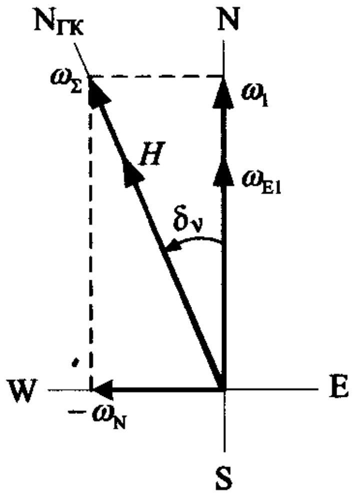
$$\omega_N = \frac{V_N}{R}; \qquad \omega_E = \frac{V_E}{\tilde{R}\,cos\varphi}.$$

From Fig. 3.10 it follows that the vector of the vessel's angular velocity along the parallel $\boldsymbol{\omega_E}$ coincides in direction with the vector of the angular velocity of the Earth's rotation $\tilde{\omega}$. Therefore, we can decompose vector ω_E into components in the same way as it is done with a vector $\tilde{\omega}$. The result is as follows:

$$\omega_{E1} = \omega_E\, cos\varphi = \frac{V_E}{\tilde{R}}; \qquad \omega_{E2} = \omega_E sin\varphi = \frac{V_E}{\tilde{R}}\,\mathrm{tg}\varphi;$$

Thus, three components of angular velocities turned out to be in the plane of the true horizon: ω_1, ω_{E1} and $-\omega_N$ (Fig. 3.11).

The main axis of the gyrosphere will be set according to the resulting ω_Σ vector, that deviates from the plane of the true meridian by angle δ_v, called the speed error. This plane is called the plane of the gyrocompass meridian.



Let us determine the angular deviation δ_v of the axis of the sensitive element from the plane of the true meridian (sign "–" before ω_N means that the angle has a western direction.

$$tg\ \delta_v = -\frac{\omega_N}{\omega_1+\omega_{E1}}; \qquad 3.5$$

after substitution the values we get:

Fig. 3.11. Gyro speed error

$$tg\ \delta_v = -\frac{V_N/\tilde{R}}{\tilde{\omega}\ cos\varphi + V_E/\tilde{R}} = -\frac{V_s \cos TC}{\tilde{R}\ \tilde{\omega}\ cos\varphi + V_s \sin TC} \qquad 3.6$$

It is clear from the formula that the speed error has a semicircular character, as shown in Fig. 3.12. The figure also shows the addition of the vectors ω_N and ω_{E1} with the vector ω_1 for the main headings.

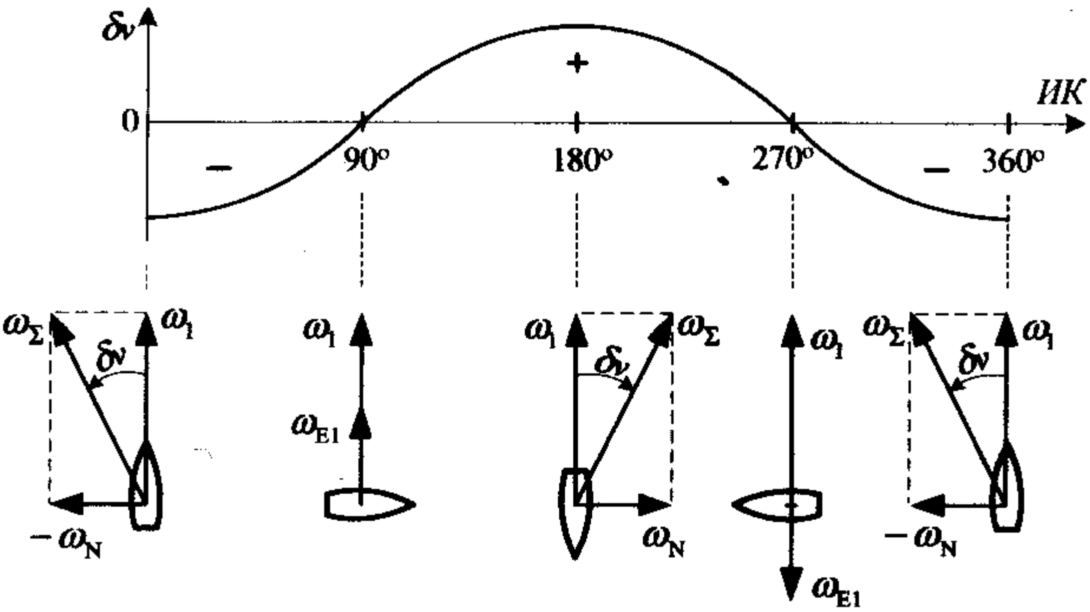


Fig. 3.12. Dependence of speed error on the true course

It is convenient to express the speed error formula as a function of the gyrocompass course. To do this, we express tgδ_v as a ratio $sin\delta_v/cos\delta_v$ and use the well-known general relationship:

$TC = GC + \delta_{GC}$;

After transformations, we get:

$$sin\delta_v = -\frac{V_S \cos GC}{\tilde{R}\tilde{\omega}cos\varphi};$$

At speeds not exceeding 25 knots and sailing latitudes not exceeding 80°, the speed error has a value not exceeding 10°. Therefore, it is permissible to assume that $\boldsymbol{sin\delta_v = \delta_v}$, and taking into account the fact that $\tilde{R}\tilde{\omega}$ = 900 knots. (linear velocity of the point of the equator, due to the rotation of the Earth), we obtain a formula more convenient for its practical use directly in degrees:

$$\delta_v = -\frac{V_S\ cosGC}{900\ cos\varphi} \times 57{,}3°; \qquad 3.7$$

For example, with the initial data: Vs = 25 knots; GC = 180°; φ = 70° speed error will be: δ_v = +4.7° (4.7°E).

The basic regularities of the speed error, which follow from the analysis of formula (3.7), are as follows:

1. The speed error arises due to presence of the northern component of the vessel's speed $\boldsymbol{V_N}$. On the northern courses, the error is negative and has a western name; on the southern courses, the error is positive and has an eastern name.

2. The speed error linearly depends on the ship's speed ***Vs***.

3. Speed error has a semicircular character depending on the gyro course: it gets the maximum value on the courses of 0° and 180°; and equals to zero - on courses 90° and 270°.

4. Speed error depends on latitude according to the function ***1/cosφ = secφ***, therefore it particularly increase at latitudes above 70°.

5. The error depends on the sailing latitude, speed and course of the vessel and does not depend on any parameters of the gyrocompass and therefore it is equally inherent in all types of gyrocompasses.

During sailing, the speed error is excluded from the readings of repeaters using a corrector. It should be noted that the main axis continues to remain in the plane of the gyrocompass meridian (in the position of dynamic equilibrium), and the true course value comes from the repeaters, as a result of the corrector and the tracking system work.

In modern heading systems equipped with a microprocessor, heading information on digital and analog repeaters is free from the speed error - correction is performed continuously and automatically.

3.5. The gyrocompass behavior during maneuver

When maneuvering a vessel (changing its speed, heading, or both at the same time), the inertia torque arise that cause the appearance of inertial error. The strongest effect on the sensitive element of the gyrocompass is exerted by the linear acceleration component acting along the meridian.

We will assume that the ship is maneuvering by changing its speed (let the speed increase from slow speed to full speed forward) along the meridian in a northerly direction.

In Fig.3.13 is shown a single-gyroscope model of the SE - a gyrosphere with a displaced center of mass at point G. Prior to the start of the maneuver, the X-X axis of the sensitive element was in the equilibrium position, indicating the plane of the gyrocompass meridian Nk1, while it was deviated from the true meridian by the speed error angle $\boldsymbol{\delta v_1}$ corresponding to the beginning of the maneuver.

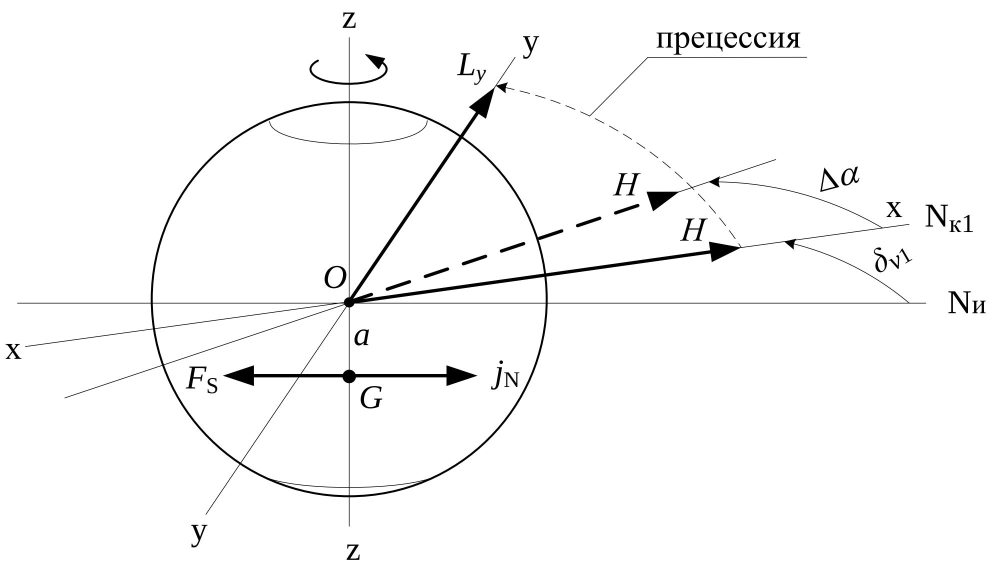


Fig. 3.13. Inertial shift of the SE main axis

The acceleration vector $\boldsymbol{j_N}$ is directed towards N_T. The force of inertia F_S caused by acceleration $\boldsymbol{j_N = \dot{V}_N}$ is applied to the center of mass of the SE, is always pointed in the direction opposite to the acceleration and is equal in magnitude $F_S = -m\dot{V}_N$ (according to Newton's second law) , where ***m*** is the mass of the SE.

The distance ***a*** (metacentric height) from the suspension point of the gyrosphere ***O*** to the point ***G*** is the arm of the force $\boldsymbol{F_S}$ acting around the Y–Y axis of the SE, therefore, the torque of this force $\boldsymbol{Ly = F_S \times a}$ is created.

After substitution the value of $\boldsymbol{F_S = -m\dot{V}_N}$ we get:

$$\boldsymbol{L_y = -m\dot{V}_N \times a = -mga\frac{\dot{V}_N}{g} = -\frac{B}{g}\dot{V}_N}\ , \qquad 3.8$$

The torque vector ***Ly*** coincides with the Y–Y axis and directed to West (so that from the end of the vector ***Ly*** the action of the force $\boldsymbol{F_S}$ is observed counterclockwise). This torque causes precession of the SE around the ZZ axis: the vector ***H*** tends to the vector ***Ly*** in the horizontal plane by the shortest way.

The precession movement of the SE, which occurs under the action of inertia torque, is called inertial precession.

To determine the angular velocity of the inertial precession, we use the well-known formula:

$$\omega_p = \frac{L_y}{H} = -\frac{B}{Hg}\dot{V}_N, \qquad 3.9$$

Due to inertial precession, which take place only during the maneuver time ***Δt*** (and after the end of the maneuver it stops), the main axis of the SE will turn in the horizontal plane by a certain angle ***Δα***. This angle is called the ***inertial displacement*** of the gyrosphere and its value calculates as follows:

$$\Delta\alpha = \omega_p \times \Delta t$$

and after substitution the value ω_p we get:

$$\Delta\alpha = -\frac{B}{Hg}\dot{V}_N\Delta t = -\frac{B}{Hg}(V_{N2} - V_{N1}) = -\frac{B}{Hg}\Delta V_N, \qquad 3.10$$

since the acceleration $\Delta\dot{V}_N = (V_{N2} - V_{N1})/\Delta t$ is the difference in the vessel's speed along the meridian during the time from the beginning of the maneuver $\boldsymbol{t_1}$ to its end $\boldsymbol{t_2}$.

$\Delta\boldsymbol{V_N} = V_2 cosCC_2 - V_1 cosCC_1$ is the difference in the ***northern component of the ship's speed*** during the maneuver ***Δt***.

The "minus" sign means that the inertial movement occurs to the west. After the completion of the maneuver, the vector ***H*** of the SE angular momentum will indicate the new position of the compass meridian $\boldsymbol{N_{k2}}$.

Aperiodic transition and its condition

Any maneuver of the vessel causes its horizontal acceleration. The pendulum gyrocompass is affected only by the meridional component of this acceleration.

Before the moment $\boldsymbol{t_1}$ of the beginning of the maneuver, the position of the dynamic equilibrium of the gyrocompass is characterized by the value of its speed error $\boldsymbol{\delta_{v1}}$, and after the moment $\boldsymbol{t_2}$ of the completion of the maneuver, by the value $\boldsymbol{\delta_{v2}}$. So, during the maneuver from $\boldsymbol{t_1}$ to $\boldsymbol{t_2}$, the equilibrium position changes by the angle:

$$\Delta\delta v = \delta v_2 - \delta v_1 \qquad 3.11$$

At the same time, there is an inertial shift of the main axis of the gyrocompass in the same direction by an angle Δα. Therefore, by the end of the maneuver at $\boldsymbol{t_2}$, one of three cases is possible:

1) $\Delta_\alpha < \Delta\delta_v$ 2) $\Delta_\alpha = \Delta\delta_v$ 3) $\Delta_\alpha > \Delta\delta_v$

First consider case 2, which is the most favorable for navigation. In this case, the inertial shift of the sensitive element during the maneuver is equal to the change in speed error during the same time.

The fulfillment of this condition means that by the end of the maneuver, the sensitive element is in a new equilibrium position corresponding to the new value of the speed error and no further oscillations of its main axis occur. Such a transition of the sensitive element of the gyrocompass to a new position of dynamic equilibrium is called ***aperiodic transition.***

The process of aperiodic transition is shown in Fig. 3.14 with a solid line passing through point 2 and indicating the direction of the compass meridian Nk_2.

Condition of aperiodic transition is as follows:

$$\boldsymbol{\Delta\alpha = \Delta\delta v} \qquad 3.12$$

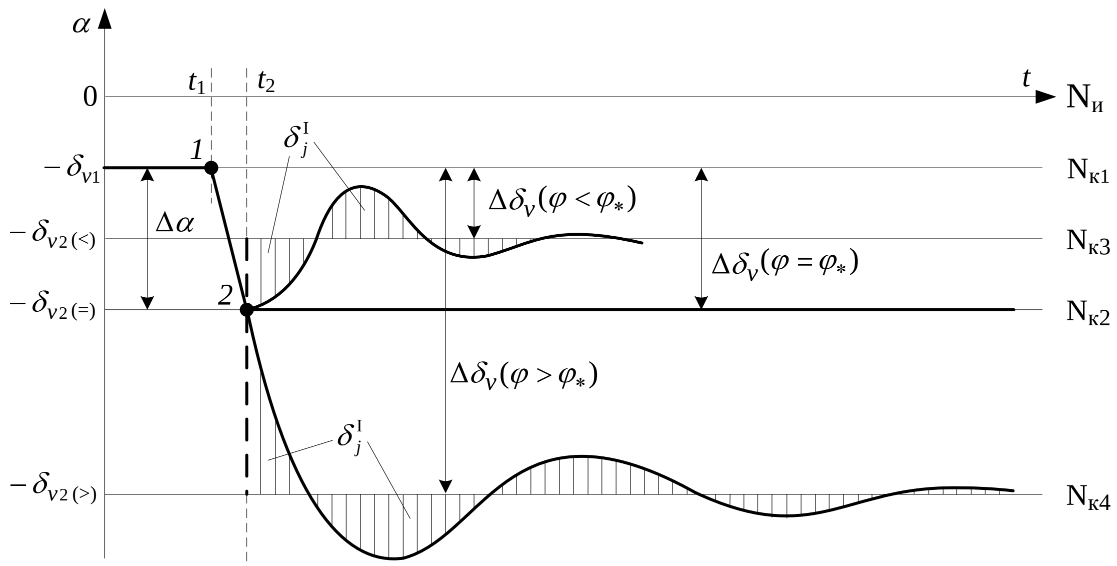


Fig. 3.14. Aperiodic transition and inertia error of the I type

The condition of aperiodic transition can be presented in a more informative form. To do this, we substitute the values of the expressions in the left and right sides of formula 3.12. The expression in the left side is represented by formula 3.10

The expression in the right side is the change in speed error during the maneuver (we use formula (3.7):

$$\Delta\delta_v = \delta_{v2} - \delta_{v1} = -\frac{V_2 \cos KK_2}{\widetilde{R}\,\widetilde{\omega}\cos\varphi} + \frac{V_1 \cos KK_1}{\widetilde{R}\,\widetilde{\omega}\cos\varphi} = -\frac{\Delta V_N}{\widetilde{R}\,\widetilde{\omega}\cos\varphi}, \qquad (3.13)$$

After substitution we get:

$$-\frac{B\Delta V_N}{Hg} = -\frac{\Delta V_N}{\widetilde{R}\widetilde{\omega}\cos\varphi}. \qquad (3.14)$$

Transforming expression (3.14) according to the property of proportions, then taking square roots from the right and left sides of the resulting equality and multiplying the result by 2π, we get:

$$2\pi\sqrt{\frac{H}{B\,\widetilde{\omega}\cos\varphi}} = 2\pi\sqrt{\frac{\widetilde{R}}{g}}. \qquad (3.15)$$

On the left side of equality (3.15) there is a well-known expression for the period $\boldsymbol{T_o}$ of natural continuous oscillations of the GC. On the right side there is an expression that can be interpreted as the period ***T**** of natural continuous oscillations of a mathematical pendulum, the length of the thread of which is equal to the radius of the Earth.

Thus, in order for the main axis of the SE to move from the equilibrium position before the maneuver to a new equilibrium position after the maneuver without making any oscillations, it is necessary and sufficient to make the period of natural oscillations of the GC equal to the oscillation period of the mathematical pendulum, the length of the thread of which is equal to the Earth radius.

If we substitute in the formula 3.15 $\widetilde{\boldsymbol{R}} =$6378 km and $\boldsymbol{g}$ = 9,81m/s^2, then we get the Schuler period equal to ***T**** = 84,4 min

This condition, which is of great importance in the theory and practice of gyrocompasses, was established in 1910 by a German scientist, Professor Max Schuler (1882 - 1972) and therefore this condition is often called the condition (theorem) of M. Schuler.

If the period of continuous oscillations T_o of the gyrocompass is equal to the Schuler period T* = 84,4 min then its transition to a new position of dynamic equilibrium after the maneuver occurs aperiodically.

It can be seen from formula (3.15) that an aperiodic transition can only be performed at a certain designed latitude φ*. The designed latitude of Russian-made gyrocompasses is φ* = 60° In Germany, φ* is taken equal to 54°, in England - 52°, in the USA - 40°.

3.6. Gyrocompass inertial errors

Inertial error of the first kind

Most gyrocompasses are non-aperiodic and for them, as was established above, the condition of an aperiodic transition is satisfied only at the designed latitude $\boldsymbol{\varphi^*}$.

When a vessel maneuver in any other latitude $\boldsymbol{\varphi}$ not equal to $\boldsymbol{\varphi^*}$, we have:

$$\boldsymbol{To \neq T^*} \quad \text{and} \quad \boldsymbol{\Delta\alpha \neq \Delta\delta_v}.$$

If the maneuver conditions are unchanged, then the inertial shift $\boldsymbol{\Delta\alpha}$ will be the same at any latitude and the main axis will be in the position determined by point 2 (Fig. 3.15), however, $\boldsymbol{\Delta\delta v}$ also depends on the navigation latitude.

Then, after the completion of the maneuver in latitude $\varphi < \varphi^*$, the main axis, making damped oscillations, will tend to the established value of the velocity deviation $\delta v_2(<)$, that is, to a new position of dynamic equilibrium Nk_3, and in latitude $\varphi > \varphi^*$ - to $\delta v_2(>)$ - to the meridian $N\kappa_4$. There is a variable inertial error of the first kind $\boldsymbol{\delta j^I}$ (shaded area in Fig. 3.15).

Finally we get: $$\delta_j^{\mathrm{I}} = \Delta\alpha - \Delta\delta_v = -\frac{B\Delta V_{\mathrm{N}}}{Hg} + \frac{\Delta V_{\mathrm{N}}}{\tilde{R}\,\tilde{\omega}\cos\varphi}. \qquad (3.16)$$

After simple transformations of expression (3.16) and taking into account formula (3.15), we obtain:

$$\delta_j^{\mathrm{I}} = (\delta_{V2} - \delta_{V1})\left(\frac{T_*^2}{T_o^2} - 1\right). \qquad (3.17)$$

This version of the formula for $\boldsymbol{\delta j^I}$ most clearly reflects the reason for the appearance of the inertial error of the first kind, - an inequality between the period $\boldsymbol{T_o}$ of the gyrocompass and the period of Schuler $\boldsymbol{T^*}$.

The sign of the inertial error $\boldsymbol{\delta j^I}$ depends on the difference in the values of speed errors at the end and at the start of the maneuver, as well as on the difference between the latitudes of navigation and the designed one.

The main features of the inertial error of the first kind are as follows:

1. It occurs due to the forces of inertia that arise during maneuvering, and is determined by the lowered center of mass of the SE.

2. It takes place in non-aperiodic GC, if the ship maneuvers not in the design latitude $\boldsymbol{(\varphi \neq \varphi^*)}$ so that the northern component $\boldsymbol{\Delta V_N}$ of its speed changes.

3. Occurs at the beginning of the maneuver, increases almost linearly and reaches its maximum value at the end of the maneuver.

4. The maximum value is proportional to the value of ΔV_N and the greater, the more the latitude of the ship's position φ differs from the designed φ^*, and the sign of this value is the same as the sign of ΔV_N at $\varphi > \varphi^*$.

5. It has the greatest value when the vessel turns from course N to course S and vice versa; in these cases, on high-speed vessels and in high latitudes, it can be 5° - 6° and more.

6. After the completion of the maneuver, δj^I decreases oscillatoryly with the period of damped oscillations ***Td*** under the action of an oil damper.

Inertial error of the second type. The liquid in the damper vessels under the action of inertial forces affects the transition of the main axis to a new position of dynamic equilibrium and, therefore, leads to errors in the GC readings.

The error that occurs during the vessel's maneuver due to working oil damper in the sensitive element of the gyrocompass is called inertial error of the second type.

Suppose the ship perform the same maneuver as in the previous example (Fig. 3.14) but this occurs at the designed latitude $\varphi^* = 60°$. Then $\delta_j^I = 0$ (inertial error of the first type don't exist). The main axis of the SE should make an aperiodic transition to a new position of the gyroscopic meridian Nk_2 - to point 2, as shown in Fig. 3.15.

At the same time, since the damper vessels are not blocked, under the action of inertia forces F_S, the oil begin to flow from the northern vessel to the southern one. In the southern vessel, the excess of oil will gradually increase, the gravity torque of which L_{oil} acts in the same way around the Y–Y axis, but in the opposite direction to the torque L_y. Consequently, the speed of inertial movement (under the action of the torque L_y) will slow down and the main axis of the SE will not reach the new position Nk_2 by the end of the maneuver, but will take a position at point 3 (Fig. 3.15). An inertial error of the second type δ_j^{II} will appear in the gyrocompass readings.

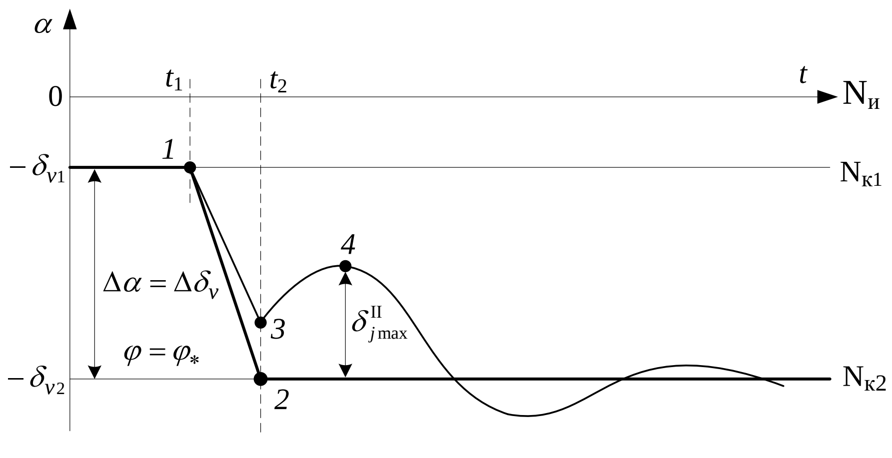


Fig. 3.15. Inertial error of the II type

The existing excess of liquid in the southern vessel will still create a torque L_{oil}, which will gradually (due to the viscosity of the liquid and the design of the damper) decrease, but at the same time retain its former sign.

During a quarter of the period *(T_d/4)*, the axis of the gyrosphere will move farther and farther towards the initial position of the gyroscopic meridian Nk_1, reducing the speed of its movement. Due to the equalization of the oil levels in the damper vessels, the indicated movement will stop (point 4); the inertial error of the second kind reaches its maximum value $\delta_J^{II}{}_{\max}$. In this position, the consequences of the maneuver disappear and the main axis, making damped oscillations, will come to a new position of the gyroscopic meridian Nk_2.

The inertial error of the second kind under normal navigation conditions does not exceed ± 0,5°, however, on high-speed vessels and with significant changes in course (speed), it can reach 5°. To eliminate it, in some designs of gyrocompasses, a damper switch is provided that blocks the connecting tube between the damper vessels for the duration of the maneuver.

Main features of the inertial error of the second type:

1. The reason for appearance is the open switch in the tube connecting the oil damper's vessels.
2. The maximum value in time - about a quarter of the damped oscillations period (Td/4) after the end of the maneuver - lagging error.
3. The value depends only on the parameters of the maneuver and does not depend on the latitude of the place. The maximum is always directed towards the original gyrocompass meridian
4. Exist in "pure" form in a non-aperiodic gyrocompasses during the maneuvering in the designed latitude.
5. Prevention of occurrence is ensured by closing the oil damper switch for the duration of the maneuver: if $\varphi > \varphi$ *, then the use of a damping switch is advisable; if $\varphi < \varphi$* then using this switch is inefficient.

Total inertial error. As a rule, two-gyroscope GCs in operation on ships are not aperiodic and, moreover, not all of them have a damp switch. This means that in the general case, during maneuvering, inertial errors of both the first and the second kind will occur simultaneously in the readings of the GC.

The sum of inertial errors of first and second kinds is called the total inertial error δ_J^{Σ}, which should be taken into account for a certain time interval after the completion of the maneuver.

A detailed study of δ_J^Σ shows that its value depends on the ratio of the designed $\boldsymbol{\varphi^*}$ and the actual $\boldsymbol{\varphi}$ latitudes of the maneuver.

At latitude $\boldsymbol{\varphi < \varphi^*}$, the errors δ_J^I and δ_J^{II} during the first quarter of the period of damped oscillations are opposite in sign and close in magnitude, so they will cancel each other out. Therefore, at latitudes lower than the designed one, it is inexpedient to close the damper switch for the duration of the maneuver.

If $\boldsymbol{\varphi > \varphi^*}$, then during the first quarter of the error period values δ_J^I and δ_J^{II} have the same signs and the total error can be quite noticeable. In this case, it is advisable to close the damper switch during maneuver.

The total inertial error can reach significant values at high latitudes. It is of practical interest only during the first half-period of damped oscillations, then slowly decreases due to the large period of damped oscillations of the gyrocompass and becomes insignificant.

A typical graph of the total inertial error (IE) of the «Курс-4» gyrocompass during a maneuver at a latitude of 75°, consisting in a speed increase from 0 to 25 knots on a heading of 180° for 360 seconds, is shown in Fig. 3.16.

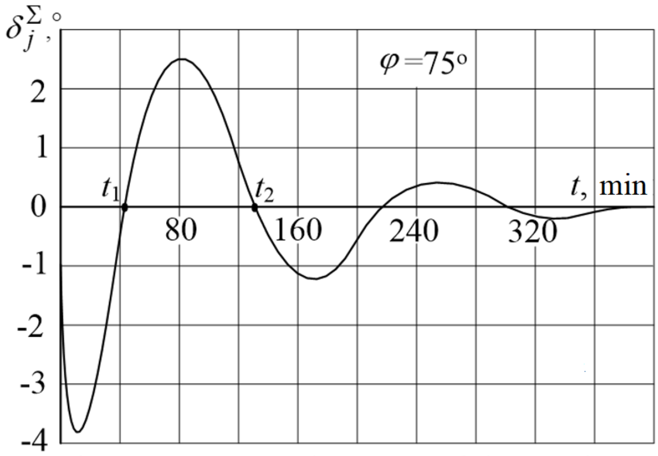


Fig. 3.16. Example curve of the total IE

The initial phase of the damped oscillations δ_J^Σ, as well as its magnitude and sign at the moment of completion of the maneuver, depend not only on the navigation latitude, as was said, but also on the parameters of the maneuver. Therefore, in each particular case, the curve δ_J^Σ can start both from the negative or positive values, as well as from zero.

Of particular interest is the effect of repeated maneuvers on the readings of the gyrocompass. Such a sequence of maneuvers is possible, in which the resulting error can reach its maximum value, which is 2–2.5 times greater than the value of $\boldsymbol{\delta j}$ during a single maneuver. The total error is the result of the superposition of all components $\boldsymbol{\delta j}$, taking into account the time of occurrence of each. At high latitudes, δ_J^Σ can reach 10° or more. This can happen when maneuvering along the meridian where ΔV_N is greatest at a given speed. The simplest way to estimate the influence of δ_J^Σ is to preliminarily calculate the change in the meridional component of the ship's speed before the maneuver using the formula

$$\Delta V_N = V_2 \cos KK_2 - V_1 \cos KK_1,$$

where V_2, KK_2 and V_1, KK_1 – are the values of the ship's speed and heading, respectively, after and before the maneuver.

If $\boldsymbol{\Delta V_N}$ = 5 - 7 knots, then the total GC inertial error is insignificant and may not be taken into account. If $\boldsymbol{\Delta V_N}$ > 7 kt, then δ_j^{Σ} should be taken into account, which will be discussed in more detail below.

Accounting for the total inertial error. ***The total inertial error of the GC resulting from maneuvering should be taken into account when fixing the ship's position using GC or radar bearings (the GC is connected to the radar).***

Let, when fixing the ship's position by two bearings, $\boldsymbol{M_o}$ is the true ship position (Fig. 3.17), in which the lines of position (opposite true bearings) is intersected at an angle θ.

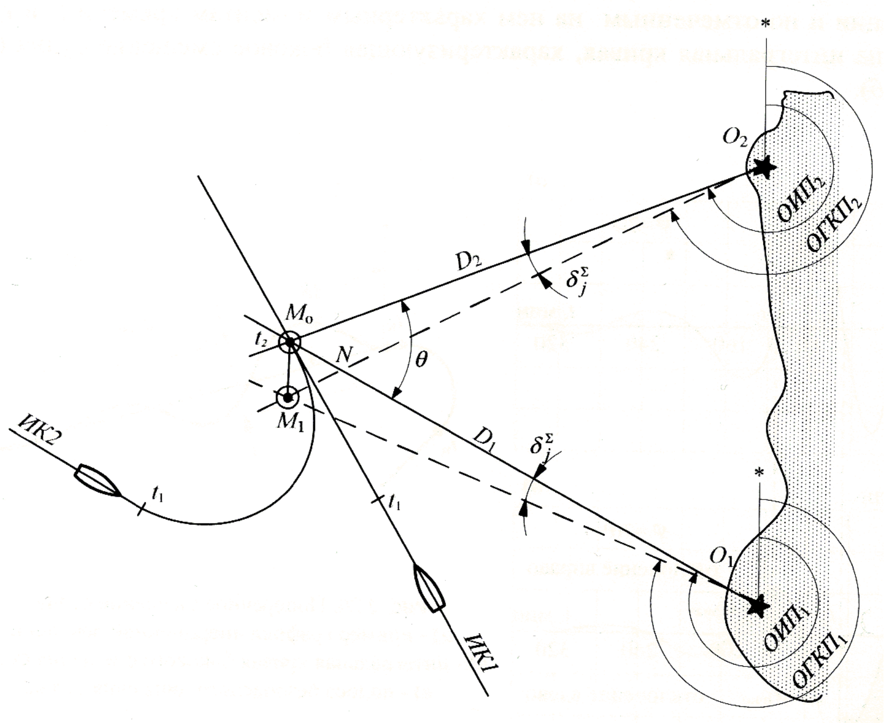


Fig. 3.17. Total inertial error effect on ship's fix position

The radial root mean square error (RMS - 68% probability) of fixing this point is estimated by the formula [8].

$$M = \frac{m_{\text{ГКП}}}{57{,}3 \sin\theta} \sqrt{D_1^2 + D_2^2}\,, \qquad (3.18)$$

where: $m_{\text{ГКП}}$ is the root mean square (RMS) error of gyrocompass bearing;

θ is the angle between bearings;

D_1 and D_2 are distances to the landmarks (reference points).

Let's take an example. Distances to landmarks O_1 and O_2 are equal, respectively: D_1 = 12 miles; D_2 = 15 miles; θ = 50°; $\boldsymbol{m_{GB}}$ = 0.7°. Substituting these data into (3.18), we determine that the radial RMS of the ship's position is 0,3 miles, and its doubled value of 2M (95% probability) is 0.6 miles. Point M_0 will be drawn on the map with 2M = 0.6 miles.

If the observation is made soon after the maneuver, then the results of bearing measurements will be burdened by the error δ_J^Σ. On the map, point M_1 will be obtained, with the already mentioned RMS, and the estimated position of the vessel will receive an offset of the observation M_oM_1.

For example, we consider that immediately after the completion of the maneuver, the total inertial error is 4,0°. With the same values of D_1 = 12 miles, D_2 = 15 miles and the angle between the bearings θ = 50°, the magnitude of the M_oM_1 observation shift, due to the influence of only the inertial error, will equal 0.8 miles.

Since the actual value of δ_J^Σ in real navigation conditions is unknown, this type of observation is recommended to do before the maneuver or 1,5 – 2,0 hours after it.

Vessel transverse shift. As a result of the vessel's maneuver the total inertial error occurs in the GC readings which exists for a certain time. All this time the vessel, controlled by the gyrocompass, follows the wrong course - different from the specified one. Under such conditions, the ship lateral shift relatively to the course line plotted on the map will inevitably appears.

If, for example, we use the graph of the total inertial error δ_J^Σ, shown in fig. 3.16, then in the first half-period of its change, by the time t_1, since the error has a constant negative sign, the ship's shift reaches the maximum value d_{1max}, in this case to the left of the intended path.

By the time t_2, due to the fact that the error changes its sign, not only the entire shift that has arisen by the time t_1 is compensated, but also reaches the maximum shift value $d_2$max of the opposite sign. Subsequent maxima are small and can be ignored.

Therefore, if after maneuver the given course is controlled according to the gyrocompass, the vessel will deviate in both directions from the course line, capturing a lane, which is called a drift lane or a safe lane.

This must be taken into account especially when sailing in cramped conditions, for example, in narrow places, shallow areas or near sunken objects.

Practical recommendations for reducing the effect of the total inertial error of the gyrocompass on the accuracy and safety of navigation.

1. It is most expedient to determine the gyrocompass correction by the landmarks when the ship is moored at berth.

2. A systematic check of the GC correction stability should be carried out during navigation under conditions when the ship is at least 1.5 - 2.0 hours, and in high latitudes at least 3.0 hours proceed a constant course at a constant speed.

3. Comparison of the readings of the gyrocompass and the magnetic compass should be performed immediately after the end of the turn in order to know the correction of the magnetic compass, at least up to the value of the inertial error, if the gyrocompass fails. Then, the comparison of readings should be performed after 1.5 - 2.0 hours and the resulting correction of the magnetic compass should be taken into account in future.

4. Within 1.5 - 2.0 hours after the maneuver, one should not rely on observations on two bearings, giving preference to fix position methods that do not depend on the gyrocompass, for example, by radar distances.

5. It should be avoided, especially when sailing at high latitudes, repeated maneuvers following one after another at time intervals close to the half-period of the damped oscillations of the gyrocompass.

6. Bearing in mind the occurrence of ship’s transverse shift after maneuver, it should, if possible, carry out the last maneuver before entering narrowness or constrained waters so far in advance that the maximum linear shift of the vessel occurs before entering the indicated areas.

The total inertial error should be taken into account if, during the maneuver, the change in the northern component of the ship's speed ΔV_N is at least 5-7 knots. With a smaller value of ΔV_N, the influence of the ship's maneuver on the gyrocompass becomes insignificant.

Application of mathematical models for compensation of inertial errors.

In order to improve the accuracy of two-gyroscope pendulum gyrocompasses, the company “Anschutz”, Germany, created the Nautocourse correction system, which is used in Standard 20/22 gyrocompasses [3].

The idea of the method for increasing the accuracy is that the passport parameters of the sensitive element of the given gyrocompass are preliminarily entered into the microprocessor. Based on the instantaneous values of inertial error calculated during the ship’s maneuver with help of a microprocessor, the readings of all repeaters are continuously corrected. In this case, there is no effect on the sensitive element of the gyrocompass, i.e., its complete autonomy is preserved.

At the same time, the speed error of the gyrocompass is calculated and also excluded from the readings of the repeaters.

3.7. Influence of rolling on the gyrocompass accuracy

The error formation process. Let us consider the influence the rolling only on the sensitive element of a single-gyroscope GC with a lowered center of gravity. We believe that the rolling occurs according to the harmonic law.

In the process of rolling, linear accelerations ***jk*** occurs. The acceleration vector is located in the plane of oscillations perpendicular to the for-and aft plane of the ship. Acceleration causes an inertial force ***Fk***, which is applied to the SE lowered center of gravity, and is directed opposite to the acceleration.

The action of inertial forces on the single-gyroscope sensitive element of the gyrocompass is shown in fig. 3.17.

When the vessel follows the course N, the inertia force F_W is arises which is directed along the parallel to the West in the first half-period. In the second half-period the inertial force has opposite direction.

The torque created by these force coincide with the direction of the sensitive element XX axis. Since the gyroscope angular momentum vector $\overline{H}$ lies on the same axis, there is no precession movement of the sensitive element. There is a rocking of the sensitive element YY axis relative to its main axis XX.

On course E (W) only meridional components F_N (F_S) of the inertia force will act, tending to rotate the SE around the YY axis. The torques created by these forces in different half-periods of rolling will alternately be directed to the E and to the W. The rolling period (7-15 s.) is many times less than the period of gyrosphere dampen oscillations. The torques L_W and L_E average value for the period is equal to zero. Therefore, with this direction of rolling, the deviation of the main axis from the meridian also does not occur. Note that the SE does not swing about the YY axis, and the position axis itself does not change.

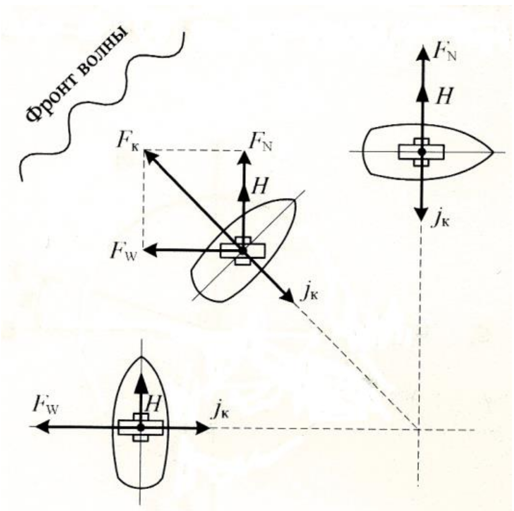


Fig. 3.18. Inertial forces and its components

Thus, we found out that on the main courses, either only longitudinal or only transverse inertia forces act on the gyroscope. The action of this forces separately from each other does not cause precession of the SE.

At intermediate courses, the components of the inertial forces act simultaneously and synchronously. The action of the inertia forces, torques and it's components on intermediate course shown in Fig. 3.18.

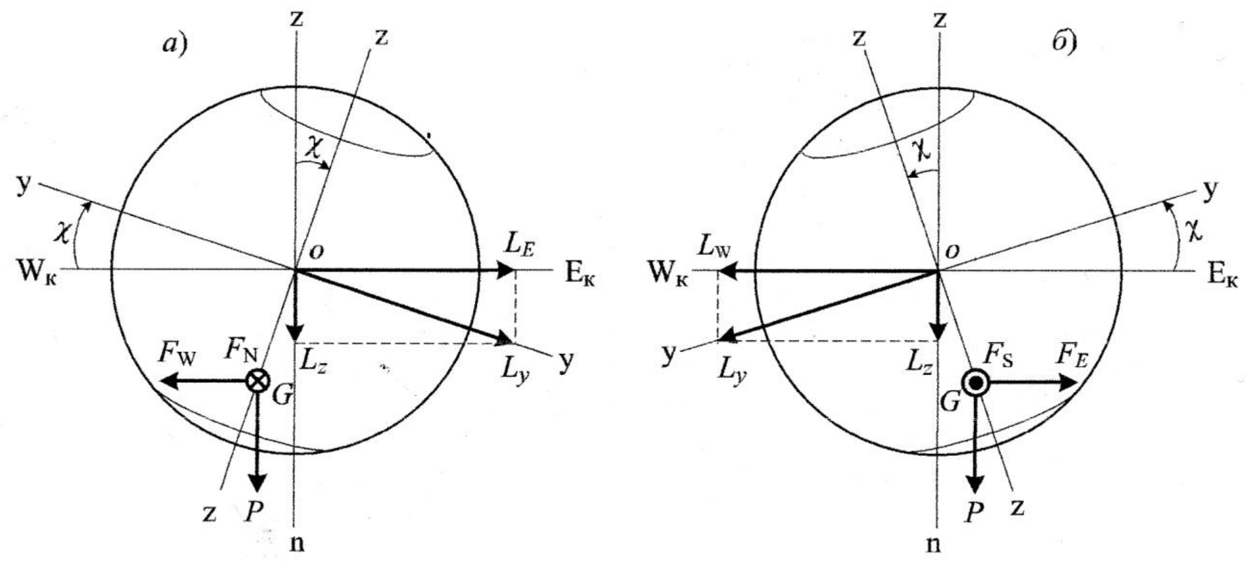


Fig. 3.19. The inertia forces and torques on the intermediate courses
a) influence of the F_N component; б) influence of the F_S component.

In Fig. 3.18, the SE is shown from the south side. The main axis XX of the gyrosphere runs perpendicular to the plane of the drawing. The southern end of the main axis is directed to the observer, and its northern end is behind the plane of the drawing.

The forces F_W and F_E turns the SE relative to the X-X axis either in one or other direction during the rolling period. The torques created by them coincides with the X–X axis, and therefore do not cause precession. The same applies to the force of gravity R.

The action of the forces F_N and F_S (shown in the figure by "a circle with a cross" - the direction behind the plane of the drawing and "a circle with a dot" - the direction towards the observer, respectively) create a torque L_y, which vector coincides with the tilted Y-Y axis. Direction of the $\boldsymbol{L_y}$ vector is determined by the right screw rule. The horizontal components $\boldsymbol{L_E}$ and $\boldsymbol{L_W}$ during each half-period of rolling act in the opposite direction. Their average value for the full period of rolling is equal to zero.

The component $\boldsymbol{L_z}$ during both half-periods has the same direction. The average value of torque $\boldsymbol{L_{zav}}$ for the period of rolling is not equal to zero. This torque will cause the precession of the gyrosphere around the Y-Y axis so that the northern end of the main axis will drop (the vector $\boldsymbol{H}$ tends to the vector $\boldsymbol{L_z}$), which means that the angle $\boldsymbol{\beta}$ of the inclination of the main axis to the horizon will change.

As a result, the SE gravity torque around the Y–Y axis changes and the gyrosphere leaves the equilibrium position in azimuth (in this case, the axis deviation will be towards E). At a certain angle of deviation of the SE from the meridian, its main axis will come to the new equilibrium position.

Deflection angle δk of the SE main axis from its equilibrium position due to ship's rolling is named the error of a single-rotor gyrocompass on rolling.

The torque $\boldsymbol{L_z}$ constantly acting during rolling can also be directed upwards - this depends on the course of the ship. Then, the main axis of the SE will rise above the horizon and the deflection angle $\boldsymbol{\delta k}$ of the main axis will be directed towards W.

Studies show that the rolling error has a quaternary dependence on the vessel's course: on the main (cardinal) courses 0°, 90°, 180° and 270° $\boldsymbol{\delta_k}$ = 0; on quarter courses 45°, 135°, 225° and 315° $\boldsymbol{\delta_k}$ is maximum.

For this reason, the deviation of a gyrocompass during rolling is more commonly referred to as the ***inter-cardinal deviation.***

The error increases with an increase in:

- the amplitude of the roll angle,
- the rolling frequency;
- the distance from the installation site of the GC to the center of the vessel's rolling;
- the latitude of the ship sailing.

Calculations and experiments have shown that the values of the intercardinal error of the GC with a single-gyroscope SE, which has a positive pendulum effect, are large and can reach 20° - 30° in real conditions. For this reason, such gyrocompasses have not been widely used.

A way to reduce the error from rolling. To prevent $\boldsymbol{\delta_k}$, it is necessary to stabilize the Y-Y axis of the device so that it remains horizontal all the time. To achieve this goal, a two-rotor gyrosphere is used in GC with a solid pendulum [3, 5].

We will not dive into the details of this issue. However, it is necessary to have a general idea of what design features of the gyrosphere provide a significant reduction in the effect of rolling on the accuracy of the gyrocompass. The design considered below is widely used in modern pendulum gyrocompasses "Standard", "Navigat" and other brands.

The sensing element of the GC is a hermetically sealed sphere, inside of which two absolutely identical gyroscopes are located, having a kinematic connection with each other. The gyroscopes are located so that the vectors of their angular momentums $\boldsymbol{H_1}$ and $\boldsymbol{H_2}$ form the same angles with the main axis of the gyrosphere X-X, equal to 45° in the middle position, and 90° to each other (Fig. 3.19 - view of the gyrosphere from above).

Brackets 2 are rigidly attached to the gyrocameras 1, facing in opposite directions. The brackets are connected by a hinged rod 3, which is connected to the body of the gyrosphere by means of two springs 4. These springs install the gyroscopes so that their main axes form an angle of 90° between them

Relatively to the gyrosphere, the gyroscopes can turn simultaneously only around their vertical axes in opposite directions and at the same angles, while the springs 4 will stretch accordingly. If the vectors $\boldsymbol{H_1}$ and $\boldsymbol{H_2}$ are decomposed into components along the axes of the gyrosphere, then it can be seen that the components H_y are directed in opposite directions and compensate each other. The components H_x are equal each other in magnitude and direction, therefore the angular momentum of the gyrosphere: ***Hg = 2Hx***

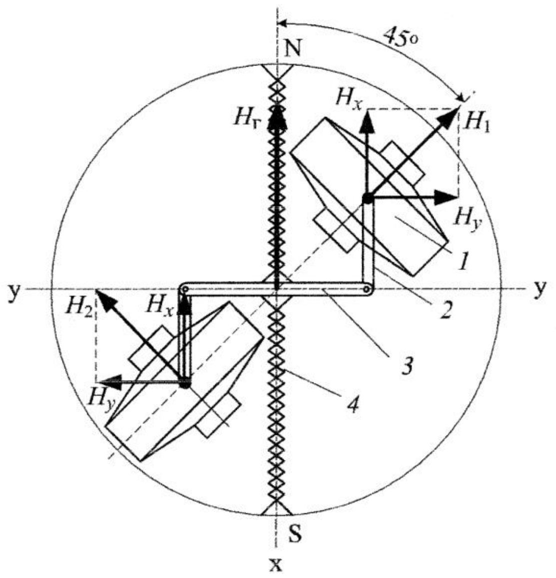


Fig. 3.20. Angular momentum

The two-gyroscope SE can be considered as a single-gyroscope with Hg = 2Hx. On this basis, the line determined by the 2Hx vector is called the main axis of the gyrosphere.

When the ship is rolling, the forces $F_{W(E)}$ every half-period (rolling period τ_k = 5–15 sec.) tend to turn the gyrosphere around the X-X axis, creating torques ***Lx***. The torques are located on the main axis X-X and also change their direction every half-period. Accordingly, the gyroscopes will periodically turn around their vertical axes ($\boldsymbol{H_1}$ and $\mathbf{H_2}$ tend to ***Lx***), which leads to stretching of the springs of the antiparallelogram mechanism.

Thus, instead of turning the gyrosphere around the main axis N-S, the inertia forces $F_{W\,(E)}$ cause the precession movement of the gyroscopes around their vertical axes in one direction or the other. Due to this, the gyrosphere acquires a significant dynamic inertia in the E-W plane, which is the stabilizing effect of gyroscopes.

The Y–Y axis of the two-gyroscope SE remains practically horizontal when the vessel is rolling, which means that the Lz component is absent and the rolling error does not occur.

The presence of 2 gyroscopes in the gyrosphere provides undamped oscillations of the X–X axis with a period T_k' of 15–20 min.

Ratio $\tau_k^2 \,/\, T_k'^2$- the coefficient of reduction of the rolling error in comparison with a single-gyroscope system is approximately 1/1000. In real conditions of navigation, the total error $\boldsymbol{\delta_k}$ for the «Курс»-type GC with significant rolling is 1.0 - 1.5°.

3.8. Examples of gyrocompasses with autonomous SE

Gyrocompasses “Standard 20/22” developed by Anschutz, Germany are the most advanced and high-precision devices in the class of two-gyro gyrocompasses with an autonomous sensitive element.

The main device shown in Fig. 3.20, on the left, is shown in section, where the gyrosphere is visible. In the upper part the electronics panel, including the navigation microprocessor is located. In the side view (Fig. 3.20, on the right) one can see a pump providing a hydrodynamic suspension of the gyrosphere (diameter 115 mm), a reservoir with a gyrosphere, a bellows suspension, an electronics panel

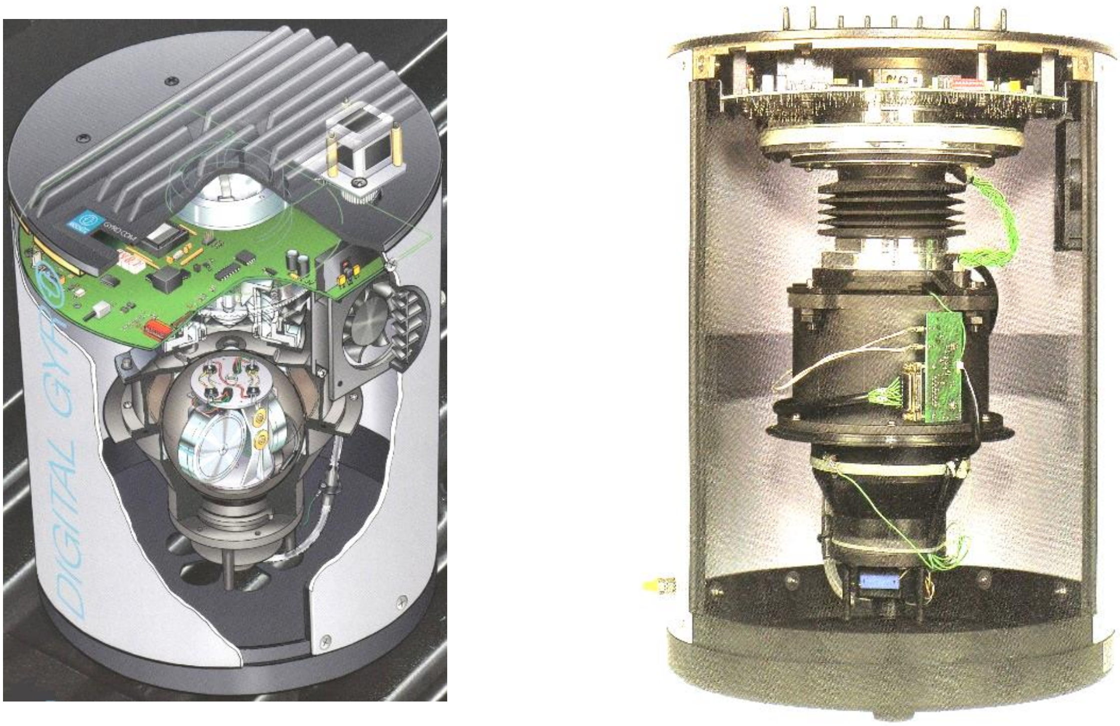


Fig. 3.21. “Standard-20” Master compass

Main technical characteristics of the “Standard 20” gyrocompass:

Static error < ±0,l° sec φ;
Dynamic error < ±0.4° sec φ:
Time of arrival to the meridian 3 hours;
Tracking system processing speed 75 °/s;
Limit of rolling & pitching angles 45°;

The Navigat X MK1/MK2 gyrocompasses developed by Sperry Marine, USA and YOKOGAWA CMZ900 (Japan) belong to the class of two-gyroscope gyrocompasses with an autonomous sensitive element having a hydrostatic suspension [7].

A significant design difference of these GC is the method of centering a gyrosphere that is immersed in a liquid in which it has positive buoyancy. In the upper part of the gyrosphere there is a cone-shaped recess. The gyrosphere is prevented from floating by a special pin mounted in the upper part of container. The lower pointed end of this pin enters the cone-shaped recess of the gyrosphere and centered its position inside the container. This method is similar to the upside down system of a magnetic compass sensitive element suspension.

The technical characteristics of these gyrocompasses are practically the same as those of the “Standard 20/22” gyrocompasses.

4. GYROCOMPASSES WITH CORRECTABLE SENSITIVE ELEMENT

4.1. Principle of operation (basic model)

Most marine gyrocompasses fall into one of two main classes: directly controlled gyrocompasses and indirectly controlled gyrocompasses.

All pendulum gyrocompasses are directly controlled gyrocompasses. These include the previously discussed gyrocompasses («Курс», «Standard», «Navigat»), and others. In these gyrocompasses, the sensitive element has the property of a pendulum. So, it reacts to the deviation of the main axis from the plane of the horizon by automatically introducing a control torque that causes SE precession towards the meridian. In these gyrocompasses, the sensitive element combines two functions:

- determine own position relative to the horizon
- creating a control torque.

Gyrocompasses in which this method of controlling the sensitive element is used are called gyrocompasses with direct control. The advantage of such gyrocompasses is their relative simplicity, and the disadvantage is the inability to correct the position of the sensitive element.

This disadvantage is overcome in gyrocompasses with indirect control.

An indirectly controlled gyrocompass is such a compass which sensitive element is an ***astatic gyroscope*** controlled by a ***torque generator*** according to a ***horizon indicator*** signal that is proportional to the angle of deflection gyroscope main axis from the horizon.

A gyroscope is called “astatic” if its center of gravity coincides with the center of suspension. Such a gyroscope does not have the properties of a pendulum and does not respond to the rotation of the horizon plane

In addition, gyrocompasses with indirect control, as a rule, are correctable, i.e. those in which the equilibrium position of the main axis of the sensitive element in azimuth and height can be purposefully changed. Correcting signals based on external information about the ship's speed and geographic latitude are generated in the gyrocompass computing device.

Gyroazimuth-compass «Вега» is a typical representative of correctable gyrocompasses with indirect control. It has two working modes:

1.Gyrocompass and

2. Gyroazimuth

In the first mode, the device operates as a corrected GC with indirect control, the main axis of which, when the ship is moving at a constant speed and heading, is located along the North-South line and indicates the plane of the true meridian.

In the second mode, the device operates as a gyroazimuth. In this case, the main axis of the device will, with a certain accuracy for a certain time interval, maintain the azimuth direction that the gyroscope indicated when it switched from the gyrocompass mode to the gyroazimuth mode.

Simplified functional diagram of gyroazimuth-compass «Вега» type is shown in fig.4.1.

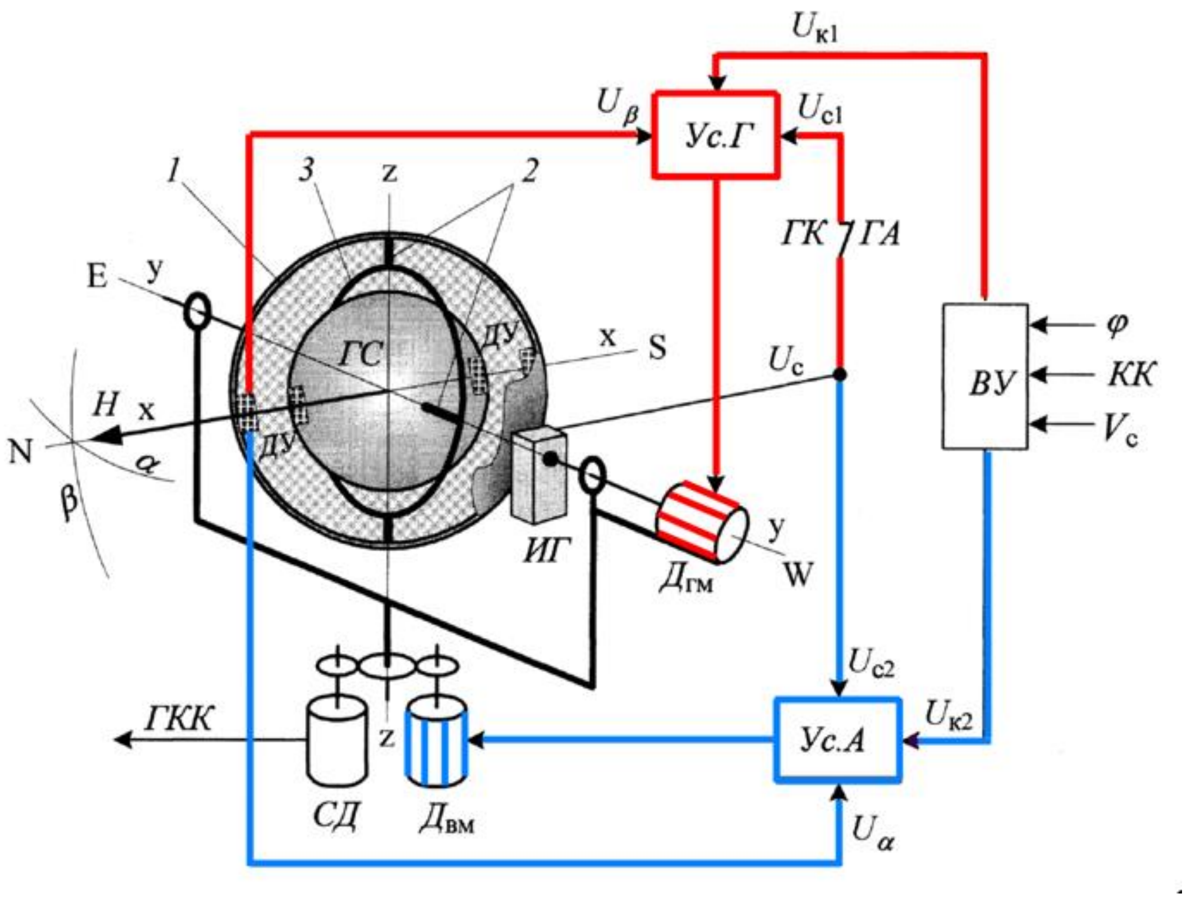


Fig. 4.1. Functional diagram of gyroazimuth-compass «Вега»

The main part of the GAC is the gyroblock, which includes: gyrosphere, suspension, tracking system.

The sensitive element is the gyrosphere (GS), inside which is placed an astatic gyroscope, which is an asynchronous three-phase motor. The ***X–X*** axis is the main one (the direction of the angular momentum vector ***H***). The center of gravity of the gyrosphere is aligned with its geometric center.

The gyrosphere is located inside the tracking sphere 1, which is a spherical groove inside the gyroblock. The entire body of the gyroblock is located in the main device of the gyrocompass and is suspended using a system of cardan rings - mounting horizontal, inner horizontal, outer vertical and has three degrees of freedom.

With respect to the tracking sphere, the gyrosphere is centered with the help of two pairs of torsion 2 - thin steel threads – two horizontal and two vertical. Horizontal torsion threads rigidly connect the gyrosphere with the intermediate ring 3, and the ring itself, by means of vertical torsion threads, has the same rigid connection with the inner surface of the tracking sphere.

In addition, through the torsion threads, a control torques are imposed on the gyrosphere and the power supply is provided to the gyromotor.

An important function in the scheme is performed by the horizon indicator (ИГ), which is an electromechanical pendulum device. It is fixed on the mounting gimbal ring directly connected to the body of the gyroblock. The sensitivity axis of the horizon indicator coincides with the YY axis of the sensitive element. Therefore, horizon indicator generates an electrical signal proportional to the angle of deviation of the gyroscope main axis ***XX*** from the horizon plane.

The functional diagram contains three servo systems: tracking, control and correction. Each of them has two channels - azimuth and horizontal. Azimuth channels are shown in blue, and horizontal channels in red.

Tracking system. On the body of the gyrosphere, the stators of two-coordinate electromagnetic angle sensors (ДУ) are installed, and their rotors are placed on the tracking sphere strictly against their stator parts. The position of the gyroscope relative to the horizontal coordinate system ***(ONEn)*** is determined by the angles α and β, and the position of the tracking sphere is determined by the angles α_s and β_s. Then, measured by the angle sensor, the misalignment angles of the tracking sphere and the gyrosphere in azimuth will be $(\alpha - \alpha_s)$, in height - $(\beta - \beta_s)$.

In order for the gyrosphere to be free from external moments, it is necessary to keep the torsion threads constantly in the untwisted state. For this purpose, the gyroazimuth-compass has two-channel tracking system, which consist of:

– azimuthal channel, including angle sensor (***ДУ***) in angle α, amplifier ***Ус.А*** and vertical torque generation motor ($Д_{ВМ}$);

- horizontal channel, including angle sensor (***ДУ***) in angle β, amplifier ***Ус.Г*** and horizontal torque generation motor $Д_{ГМ}$;

When the gyrosphere is misaligned with the tracking sphere, signals are taken from the outputs of the angle sensors ***(ДУ)*** are as follows:

$$U_\alpha = k_{AS}\,(\alpha - \alpha_s); \quad \text{and} \quad U_\beta = k_{AS}\,(\beta - \beta_s),$$

where k_{AS} is the transmission coefficient of the angle sensor.

These signals are fed through the appropriate amplifiers to the torque generation motors, which operate until the input signals become equal to zero, i.e. when the equalities $\alpha = \alpha_S$ and $\beta = \beta_S$ are satisfied.

Thus, any turn of the vessel or its yaw in waves, both around the vertical and /or horizontal axes perpendicular to the gyroscope angular momentum vector ***H***, will be immediately worked out by torque generation motors. The tracking sphere will maintain an aligned position with the gyrosphere, in which the torsion threads remain untwisted.

In such tracking system mode of operation, the sensitive element has the property of a free gyroscope, i.e. the main axis of the gyrosphere will keep its direction unchanged in inertial space.

Control system. To turn the resulting free gyroscope into a sensitive element of the gyrocompass, it is necessary to ensure continuous bringing of the SE main axis to the plane of the true meridian by imposing control torques on the gyrosphere.

For this purpose, a control electrical signal of the horizon indicator ***(HI)*** is used. The ***HI*** is a flat physical pendulum, fixed perpendicular to the ***Y-Y*** axis of the gyroblock. Its sensitivity axis is parallel to the main axis ***X-X*** of the gyroscope, so it responds both to changes in the tilt angle βc of the tracking sphere and to linear acceleration $\dot{V}_N$ due to ship maneuvering.

The scheme uses two control channels:

- horizontal - creates a horizontal torque relative to the ***Y-Y*** axis and thereby causes SE precession in azimuth - includes the horizon indicator ***HI***, amplifier ***Ус.Г***, horizontal torque generation motor $Д_{ГМ}$ and horizontal torsion threads;

- vertical - creates a vertical moment relative to the Z-Z axis and thereby causes SE precession in height, i.e. relative to the plane of the true horizon - includes the horizon indicator ***HI***, amplifier ***Ус.А***, vertical torque generation motor $Д_{ВМ}$ and vertical torsion threads;

To clarify the operation of the control system, we assume that the ship is stationary and the main axis of the gyrosphere is initially located in the meridian and is parallel to the plane of the true horizon. But, already at the next moment of time, due to the rotation of the Earth, the northern end of the GS axis will be in the eastern half of the horizon (angle α appears), which, as you know, is continuously lowering - there is a visible rise of the GS axis above the horizon - an angle β appears. The tracking system synchronously works out the resulting misalignment angles and the tracking sphere also rises in height by the angle β.

Since the horizon indicator is rigidly connected to the tracking sphere along the ***Y–Y*** axis, a signal proportional to the angle βc is taken from its output. This signal is sent to both control channels. The levels of signals (voltages) are different, they are summed up with the signals $U\beta$ and $U\alpha$ coming from the angle sensors and fed through the amplifiers to the motors. Therefore, the torque generation motors operate until the resulting signals at the input of the amplifiers become equal to zero:

As a result of the operation of the engines, the tracking sphere will be deployed relative to the gyrosphere at some angles $(\alpha - \alpha_s)$ and $(\beta - \beta_s)$, which will lead to the twisting of the horizontal and vertical torsion bars. Torsion bars have a certain stiffness - resistance to twisting. The resulting torques through the adjusting ring 3 (in the diagram of Fig. 8) will be applied to the gyrosphere along the ***Y-Y*** and ***Z-Z*** axes:

around the horizontal axis $Ly = Ay\beta$;

around the vertical axis $Lz = Az\beta$,

where ***Ay*** and ***Az*** are the modules of the horizontal and vertical torques, respectively, taking into account the rigidity of the torsion threads and the coefficient of transmission of the horizon indicator.

The torque Ly provides continuous oscillations, and torque Lz serves for oscillations damping. When a free gyroscope is acted upon by two torques, the values of which are proportional to the angle β, its main axis will continuously precess to the true meridian and simultaneously tends to take a horizontal position.

Information about the current value of the compass course ***CC*** is supplied to external consumers from the selsyn-transmitter ***СДК***, which is mechanically connected with the vertical torque generation motor $\boldsymbol{Д_{ВМ}}$.

Thus, the two-channel tracking system ensures the alignment of the tracking sphere with the gyrosphere, and the two-channel control system continuously imposes a control torque on the gyrosphere, performing the function of transforming the free gyroscope into gyrocompass.

Correction system. To correct the gyrocompass errors, correction signals $\boldsymbol{U_{k1}}$ and $\boldsymbol{U_{k2}}$ are generated in the computing device ***ВУ*** of the correction unit, which are fed into the corresponding control channels. The presence of these signals ultimately leads to additional twisting of the vertical and horizontal torsion threads, i.e. to the creation of additional compensating torques $\boldsymbol{L_{yk}}$ and $\boldsymbol{L_{zk}}$.

Information about the compass course ***КК***, ship speed ***Vc*** and sailing latitude $\boldsymbol{\varphi}$ is sent to the input of the ***ВУ***. Based on these data ***ВУ*** produces corrective voltages $\boldsymbol{U_{k1}}$ and $\boldsymbol{U_{k2}}$ that are fed to the inputs of the corresponding amplifiers and caused the creation the corrective torques $\boldsymbol{L_{yk}}$ and $\boldsymbol{L_{zk}}$.

Corrective torque $\boldsymbol{L_{yk}}$ is created by horizontal torque generation motor $\boldsymbol{Д_{ГМ}}$ and compensate so-called latitude error $\boldsymbol{\delta_{\varphi}}$ that occurs in gyro-compasses of this type.

Corrective torque $\boldsymbol{L_{zk}}$ is created by the vertical torque generation motor $\boldsymbol{Д_{ВМ}}$ for compensation the speed error $\boldsymbol{\delta_{v}}$, which inevitably occurs when the ship is moving.

As a result of the correction, the main axis of the SE in the equilibrium position will be in the plane of the true meridian and in the plane of the horizon.

The gyro-azimuth mode

In this mode the ГА/ГК switch is open and signal from the horizon indicator goes only to the vertical channel of indirect control. For this reason, the sensitive element is kept in the horizon plane but lose information about Earth rotation. However, the action of the corrective signal $\boldsymbol{U_{k1}}$ is preserved - the created moment $\boldsymbol{L_{yk}}$ ensures that the main axis of the SE follows the meridian with a certain accuracy.

This mode is used when the vessel maneuver, especially at high latitudes and at high speeds, to reduce errors caused by the action of inertia forces on the horizon indicator.

4.2. Analysis of the gyrocompass functioning

In a gyrocompass with direct control, the horizontal torque $\boldsymbol{L_y}$ method is used to dampen the sensitive element continuous oscillations (a damping moment along the ***Y–Y*** axis is created by an oil damper).

In gyrocompass with indirect control the vertical torque $\boldsymbol{L_z}$ method is used for this purpose, which causes an error arises called damping error or latitude error:

For this reason, the main axis of the indirectly controlled gyrocompass don't set exactly in the plane of the true meridian, but will be shifted in azimuth by an angle $\boldsymbol{\alpha_r}$**,** which can be received from the solution of equation (4.1).

The system of differential equations describing the main axis of the SE movement without corrective torques for a gyrocompass installed on a fixed base is as follows [2, 3]:

$$\left.\begin{aligned} &H\,\dot{\alpha} + A_y\,\beta = H\,\tilde{\omega}\sin\varphi \quad ; \\ &H\,\dot{\beta} + A_z\,\beta - H\,\tilde{\omega}\cos\varphi\,\alpha = 0\,, \end{aligned}\right\} \qquad (4.1)$$

where $\boldsymbol{A_y}$ and $\boldsymbol{A_z}$ are the modules of the horizontal and vertical torques, respectively, and are expressed in terms of the corresponding data transmission coefficients of the control channels.

The $\boldsymbol{A_y}$ module performs the function of a pendulum moment and serves to form continuous oscillations of the SE, and $\boldsymbol{A_z}$ - a damping moment and ensures the damping of these oscillations.

The position of dynamic equilibrium of the main axis of the SE. We use the system of equations (3.1). In the equilibrium position, the axis of the SE is motionless, therefore $\dot{\alpha} = \dot{\beta} = 0$. A particular solution of equations in the form $\boldsymbol{\alpha = \alpha_r = const}$ and $\boldsymbol{\beta = \beta_r = const}$ will give the result: from the first equation we find

$$\beta_{\mathrm{r}} = \frac{H\,\tilde{\omega}\sin\varphi}{A_y};$$

substituting the found value of βr into the second equation, we obtain:

$$\alpha_{\mathrm{r}} = \frac{A_z}{A_y}\,tg\,\varphi\,.$$

The presence of the angle $\boldsymbol{\beta_r}$ (rise above the horizon) ensures the angular velocity of the precessional movement of the main axis of the SE equal to the angular velocity of the meridian of the observer, therefore, the relative velocity is zero. This process of "chase" of the main axis for the meridian of the observer is continuous.

The angle $\boldsymbol{\beta_r}$ has a small value - units of arc minutes - and decreases with decreasing latitude.

However, the axis will not be set exactly in the plane of the true meridian, as was the case with a gyrocompass with an autonomous sensitive element, but will be shifted in azimuth by an angle $\boldsymbol{\alpha_r}$, which can be seen from the solution of equation (4.1).

In a gyrocompass with direct control, the horizontal moment method (an additional torque along the Y–Y axis created by an oil damper) was used to generate damped oscillations, but here the method of the vertical torque L_z is used, which leads to an error called damping error or latitude error:

$$\delta_\varphi = \alpha_r = \frac{A_z}{A_y} tg\,\varphi \,.$$

The latitude error $\boldsymbol{\delta_\varphi}$ depends on the gyro-compass design parameters - the ratio $\boldsymbol{A_z/A_y}$ and on the sailing latitude. To reduce $\boldsymbol{\delta_\varphi}$, the $\boldsymbol{A_z/A_y}$ ratio is attempted to be as small as possible (0.03 - 0.05). At high navigation latitudes, $\boldsymbol{\delta_\varphi}$, having a tangential dependence, can reach a significant value. To eliminate the latitude error, a corrective device is used.

The law of the SE main axis motion in azimuth. The operation of a gyrocompass with indirect control (without correction) installed on a fixed base is described by differential equations (4.1). The general solution of the system of equations (4.1), which determines the gyrosphere main axis movement in azimuth, has the form:

$$\alpha = A e^{-ht} \sin(\omega_d t + \psi)$$

where $\boldsymbol{A}$ is the constant of integration;

$\boldsymbol{h}$ is the damping coefficient;

$\boldsymbol{\omega_d}$ is the frequency of damped oscillations;

$\boldsymbol{\psi}$ is the initial phase.

This equality consists of a periodic term tending to zero with increasing time (Fig. 3.2, a shows a graphical interpretation of this expression). Oscillations of the SE axis are damped and their amplitude decreases according to the exponential law.

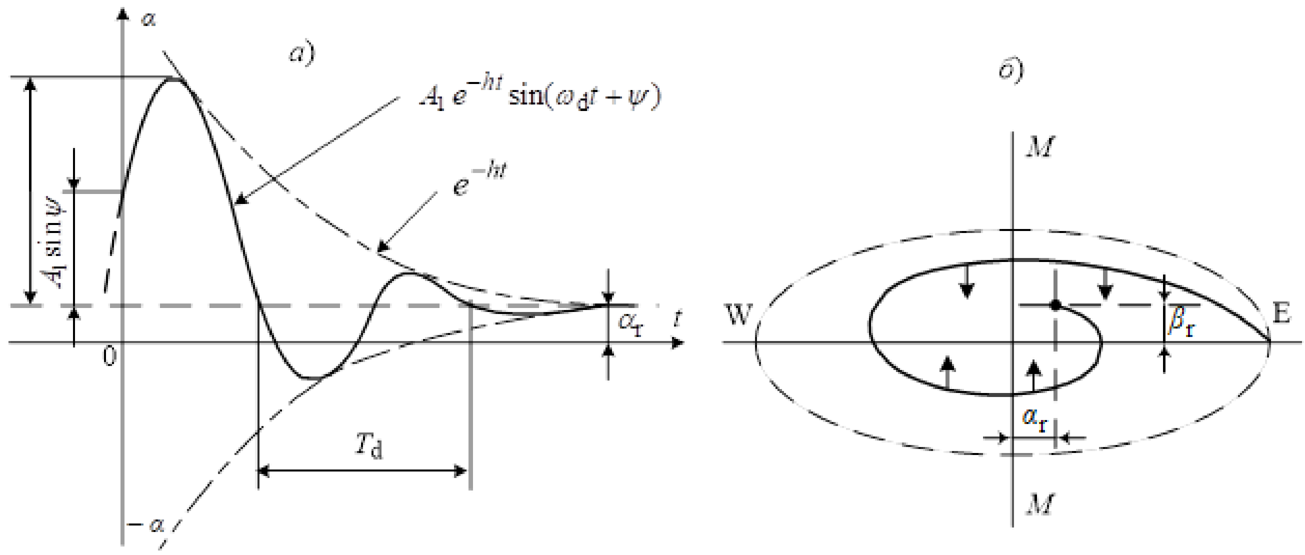


Fig.4.2. Sensitive element main axis movement
a) main axis movement in azimuth;
b) sensitive element damped oscillations curve

The damping coefficient $\boldsymbol{h}$ is determined by the formula $\boldsymbol{h = A_z/2H}$, from which it follows that it is the vertical moment that is the cause of the formation of damped oscillations, the hodograph of which is shown in Fig. 4.2 b. In the steady position, the axis will have the coordinates $\boldsymbol{\alpha_r}$, $\boldsymbol{\beta_r}$. For $\boldsymbol{A_z = 0}$ we have $\boldsymbol{h = 0}$ and $e^{-ht}=1$, i.e. we get undamped oscillations.

The period of damped oscillations is $\boldsymbol{T_d = 2\pi/\omega_d}$. For the gyroazimuth-compass «Вера» $\boldsymbol{T_d}$ = 130 - 150 min at middle latitudes, and the damping factor $\boldsymbol{f} \approx 4$.

4.3. Gyrocompass errors and ways to reduce its

Speed and latitude errors. When the ship is moving, the gyrocompass with indirect control have both a latitude error, or, as it is called, damping error $\boldsymbol{\delta_d}$, and a speed error δ_v, the same as that of a pendulum gyrocompass. In other words, in azimuth, the main axis will be deviated from the plane of the true meridian by the value of the algebraic sum of the $\boldsymbol{\delta_d}$ and $\boldsymbol{\delta_v}$ errors:

$$\alpha_r = \delta_d + \delta_v = \frac{A_z}{A_y} tg\varphi - \frac{V_N}{\tilde{R}\tilde{\omega}\cos\varphi + V_E}$$

These deviations are compensated with help of a corrective device. In the considered basic model of the gyroazimuth - compass «Вера» (Fig. 4.1), a computing device ***ВУ*** (built on sine-cosine rotating transformers) is used, to the input of which external information about the compass heading ***KK*** is supplied, and manually from the navigational console the speed of the vessel V_c and the sailing latitude φ.

The voltage U_{k1} generated in the ***BУ***, proportional to δ_d, is fed into the horizontal control channel - a compensating moment L_{ky} is created; voltage U_{k2}, proportional to δ_v, is supplied to the vertical control channel - a compensating moment L_{kz} is created. As a result, (with the timely and accurate input of the above input data), the main axis of the SE is set in the plane of the true meridian and tends to take a position parallel to the plane of the true horizon. Thus, the reading of the course of the vessel, taken from the gyrocompass repeaters, is free from the current value of the speed and latitude errors.

In modern gyrocompasses the speed and latitude errors compensation is automatically performed by a microprocessor that controls the entire operation of the gyrocompass, with continuous reception of the ship's speed V_c and latitude φ from external sources (GPS). Manual input of the specified data is also available.

Influence of accelerations during maneuvering. The horizon indicator ***(HI)*** is an electromechanical device made in the form of a flat physical pendulum, which is placed in a sealed chamber ***1*** filled with a viscous liquid ***2*** (the ***HI*** model is shown in Fig. 4.3). The pendulum is made in the form of a rod having a working body of mass ***m*** at one end. The second end of the rod is fixed to the rotor ***3*** of the angle sensor, and the stator ***4*** of the sensor is fixed to the chamber so that the pendulum can only move along a certain ***x-x*** axis, called the sensitivity axis of the ***HI***. The movement of the working fluid is limited by stops ***5***.

The horizon indicator is mounted on the tracking sphere so that its sensitivity axis is directed parallel to the main ***X-X*** axis of the gyroscope. Information about the angles of deflection of the pendulum with respect to the body of the ***HI*** chamber comes in the form of an electrical signal U_c taken from the rotor winding of the sensor

When maneuvering, the inertial forces will deflect the HI pendulum from its equilibrium position by an angle γ.

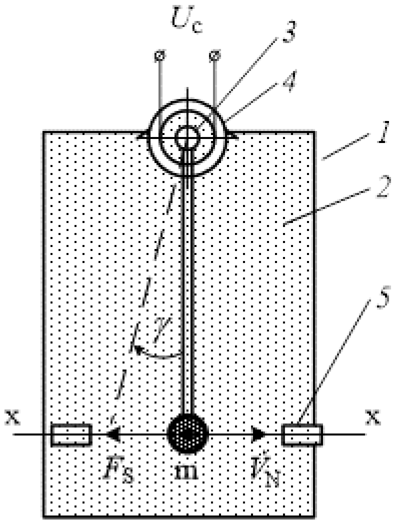


Fig. 4.3 Horizon Indicator

In this case, the deflection will occur in the same direction as when the main axis of the SE rises above the plane of the true horizon. The speed of the ***HI*** response to an external perturbation is estimated by the time constant τ_{uz} – the time interval between the beginning of the impact and its result.

In the gyroazimuth compass «Вега» τ_{uz} = 60 sec. As a result, during accelerations from the ***HI***, a signal U_c corresponding to the angle γ will be received. After its amplification and operation of the corresponding torque generation motors (Fig. 4.1) the moment $L_y = A_y \gamma$ will be applied to the SE along the ***Y-Y*** axis in the W direction, which will lead to the precession movement of the SE around the ***Z-Z*** axis with an angular velocity:

$$\omega_{pz} = -\frac{L_y}{H} = -\frac{A_y \dot{V}_N}{Hg}.$$

Integrating the last expression, we find that during the maneuver from t_1 to t_2 the main axis of the SE will move to a certain angle

$$\Delta\alpha = -\frac{A_y \Delta V_N}{Hg}. \qquad (4.2)$$

One can be convinced of the complete identity of expression (4.2) with a similar expression for a gyrocompass with an autonomous SE (2.9).

Since the readings of the gyrocompass are not burdened by speed and latitude errors, since they are compensated due to the continuous operation of the corrective device, ***the resulting displacement Δα is the inertial deviation δ_j, which fully characterizes the error of the corrected gyrocompass at the end of the maneuver.***

Reducing the influence of accelerations. Reducing the effect of maneuvering on the correctable gyrocompass is achieved by the following measures.

1. Increasing the period of continuous oscillations of the sensitive element. Turning to formula (4.2), it can be seen that, in practice, a possible decrease in the considered error can be achieved only by reducing the value of the modulus of the horizontal moment A_y.

Analyzing the behavior of the SE of the corrected gyrocompass during the stationary motion of the ship, we obtain an expression for the period of continuous oscillations

$$T_0 = 2\pi\sqrt{\frac{H}{A_y(\tilde{\omega}\cos\varphi + \frac{V_E}{\tilde{R}})}},$$

from which it can be seen that the ratio $\boldsymbol{H/A_y}$ determines its value. The inertial deviation itself is inversely proportional to this ratio.

Therefore, by increasing $\boldsymbol{T_0}$ by increasing $\boldsymbol{H}$ and decreasing $\boldsymbol{A_y}$ (as optimally as possible), a corresponding decrease in $\boldsymbol{\delta_j}$ error can be achieved.

2. Limiting the deflection angle of the ИГ pendulum by installing stops in the chamber. In the ИГ chamber (Fig. 4.3), two stops ***5*** are installed along its sensitivity axis with an optimally selected gap, which limit the pendulum deflection angles. By limiting the deflection angle of the pendulum, the magnitude of the control moments $\boldsymbol{L_{yy}}$ and $\boldsymbol{L_{yz}}$ imposed on the SE is accordingly limited. This will lead to limiting the angular velocity of the inertial precession of the SE and, ultimately, to limiting the inertial deviation of the gyrocompass**.**

3. Increasing the time constant of the horizon indicator. The value of the inertial error essentially depends on the slew rate of the signal $\boldsymbol{U_c}$ taken from the horizon indicator. The error will be the greater, the lower the damping of the working fluid of the ИГ, i.e. the smaller the ИГ time constant $\boldsymbol{\tau_{ИГ}}$.

For modern correctable gyrocompasses, including gyroazimuth-compass «Вега», the time constant $\boldsymbol{\tau_{ИГ}}$ is 60 s, which is typical for transport ships.

4. Transfer of the gyrocompass to the gyroazimuth (GA) mode. Since the main cause of the error is the inertial movement of the working body of the ИГ, turning it off for the duration of the maneuver can prevent this error. In such a situation, the device starts to work in the gyroazimuth mode, i.e. the main axis of the sensitive element of the device continues to maintain its orientation relative to the plane of the true meridian (in the presence of signals $\boldsymbol{U_{k1}}$ and $\boldsymbol{U_{k2}}$ compensation for latitude and speed errors by a corrective device).

In this case, for the period of the maneuver, the gyrocompass loses its guiding force (the horizontal control channel is turned off - Fig. 4.1) - the response of the instrument's SE to the Earth's rotation is interrupted, or, in other words, the “connection” with the Earth is lost.

The signal arising from maneuvering from the ИГ enters only the vertical control channel. But since the ratio of modules $\boldsymbol{A_y/A_z}$ is usually 0.03 - 0.05, the effect of inertial forces on the vertical control channel is insignificant. As a result, a false signal from the ИГ does not have any effect on the SE, and its main axis keeps the azimuth direction.

In this mode, the so-called "drift" of the sensitive element takes place, which is expressed in the departure of the main axis from the azimuthal (meridional) direction by no more than 1°/hour. The reasons for the drift are of instrumental origin.

The use of this method of descent δ_j is effective for vessels of any type during prolonged maneuvering, especially at high sailing latitudes.

Rolling error and how to reduce it. The single gyroscope sensitive element used in the gyroazimuth compass has some residual pendulum. This is explained by the fact that it is very difficult to achieve absolutely precise balancing of the gyrosphere during its manufacture.

The presence of the pendulum of the gyroblock leads to the buildup of SE around the axis of the suspension in time with the pitching of the vessel. At the intermediate points, the SE swings simultaneously in the N–S, E–W planes and the alternating moments $\boldsymbol{L_y}$ and $\boldsymbol{L_z}$ are applied to the gyroscope according to the signals from the horizon indicator. In this case, a constant component of the moment $\boldsymbol{L_z}$ arises along the $\boldsymbol{Z–Z}$ axis, which inevitably causes the appearance of an error in the gyro compass during rolling, the formation scheme of which is essentially the same as in pendulum compasses.

The heaving effect will be reduced if a phase shift close to 90° is made between the acceleration acting on the ИГ and the moment applied to the gyroscope. This is achieved by damping the ИГ pendulum by increasing $\tau_{ИГ}$ (by filling the ИГ chamber with a viscous liquid).

So, at $\boldsymbol{\tau_{ИГ}}$ = 60 sec. and rolling period $\boldsymbol{\tau_k}$ = 12 sec. ($\boldsymbol{\omega_k} \approx 0.5\ s^{-1}$) coefficient of error reduction from rolling $\mu \approx 900$.

The error has a quarter character and is equal to zero on courses 0, 90, 180, 270°; in quarter courses 45, 135, 225, 315° has the maximum value.

Increases with increasing sailing latitude $\boldsymbol{\varphi}$, increasing pitching amplitude θ_o and its frequency $\boldsymbol{\omega_к}$, increasing distance $\boldsymbol{l}$ to the ship's rolling center.

At pitching angles θ_o up to 15^o, the error is not more than $\pm 0.5^o$; under unfavorable conditions ($\theta o > 30^o$, $\varphi > 70^o$) is approximately $\pm 1.5^o$.

* * *

In addition to the basic model of the «Вега» gyro-azimuth compass, one can also name the «SG Brown 1000» gyro-compass, developed by Brown (Great Britain), which belongs to a correctable class gyro compass with indirect control and is designed for installation on ships of all types with speeds up to 60 knots and sailing up to latitude 80°.

Dynamically tuned gyroscopes (DNG) are becoming more and more common as sensitive elements of gyrocompasses. They are distinguished by an internal elastic suspension rotor with the motor shaft. Gyrocompasses using DNG are accurate, reliable, have small dimensions, weight and low cost.

Recently, strapdown orientation systems of the analytical type have appeared, in which optical gyroscopes are used - laser and fiber-optic. They include a microprocessor that continuously calculates the parameters of the object's orientation: heading, roll, trim speed relative to all three axes of the ship, and angular speeds of turn. Free-form systems have the following advantages: no complex mechanical elements, high accuracy of the measured parameters, increased reliability, low power consumption.

Satellite compasses are used to improve the reliability and redundancy of heading guidance. With their help, you can get information not only about the coordinates and components of the ground speed of the vessel, but also about its course. For this purpose, two or three antenna systems are used.

5. MAGNETIC COMPASSES

5.1 Earth's magnetic field

Geomagnetic and magnetic poles. In the first approximation, the Earth's magnetic field is described as the field of a uniformly magnetized ball (dipole), the magnetic axis of which makes an angle of about 11.5 degrees with the Earth's rotation axis Pn - Ps (Fig. 4.1). ***The magnetic axis*** - a straight line Pm - P′m passing through the magnetic poles - does not pass through the center of the Earth and is not its diameter. The points of intersection of this magnetic axis with the Earth's surface are called ***geomagnetic poles:*** in the Northern Hemisphere - the Canadian Arctic Archipelago, and in the Southern Hemisphere - Antarctica [11, 12].

The polarity of the Earth's magnetic field is taken such that the south magnetic pole is in the Northern Hemisphere, and the north one is in the Southern Hemisphere. It is believed that the lines of force of the Earth's magnetic field come out of the south magnetic pole, whose magnetism has a positive sign, and converge in the north magnetic pole of the Earth, whose magnetism has a negative sign.

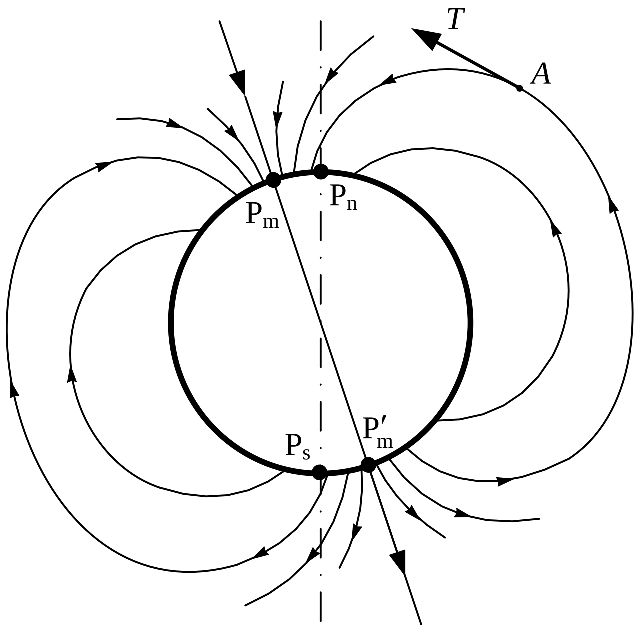


Fig 5.1. Earth magnetic field

The location of the geomagnetic poles, determined from the data of geomagnetic surveys of the Earth's magnetic field, does not coincide with the position of the geographic poles of the Earth The coordinates of the magnetic poles are calculated within the framework of various models of the geomagnetic field. One of global models, named The World Magnetic Model (WMM), are created by various international geophysical organizations, and every 5 years all data are approved and published.

According to the WMM model for 2015, the north geomagnetic pole (in fact, it is the south pole of the magnet) has the coordinates 86,3° N and 160,0° W, the south geomagnetic pole is 64,3° S, 136.6° E, the inclination of the dipole axis relative to the Earth's rotation axis is 9.63°.

These poles are drifting. Their speed has increased from 15 km per year in 2000 to 55 km per year in 2019. This rapid drift results in the need for more frequent adjustments to the navigational magnetic systems.

Geomagnetic variations. The Earth's magnetic field strength is called the ***total strength of Earth magnetism*** and is denoted by the letter ***T***. The vector T at each point of the field is directed tangentially to the magnetic field line (flux line) (Fig. 4.1). The difference between the observed value of the magnetic field strength and its average value over any long period of time, for example, a month or a year, is called geomagnetic variation. Variations are observed - daily, irregular, 27-day, seasonal, 11-year, secular. Therefore, any magnetic navigation chart must be attributed to a specific year, called the epoch of the chart.

Elements of Earth magnetism. To have an idea about the Earth magnetic field, you need to know the intensity at any point of this field. If a freely suspended ideal magnetic needle is placed at point A, then it will be aligned with its magnetic axis with the vector T, tangent to the flux line 1 (Fig. 5.2**).**

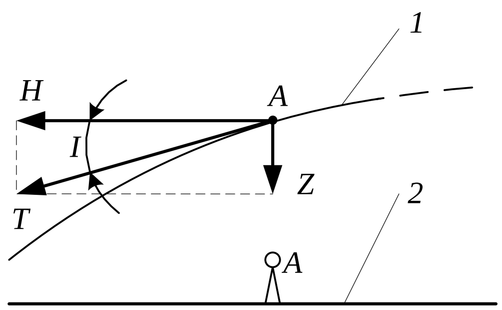


Fig. 5.2 Total strength of Earth magnetism

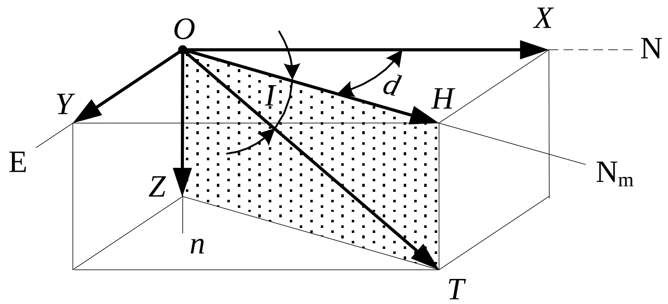


Fig. 5.3. Earth magnetism components

The decomposition of the vector ***T*** at the point of the observer ***A*** into two components gives a horizontal ***H*** parallel to the plane of horizon 2 and a vertical ***Z*** along a plumb line, depicted in the horizontal coordinate system ONEn, as shown in fig. 5.3.

Thus, we obtain the elements (vectors) of terrestrial magnetism:

T is the total strength of terrestrial magnetism. At the magnetic poles, the vector ***T*** is directed vertically, and at the north magnetic pole - down, and at the south - up.

H is the horizontal component indicating the direction of the magnetic meridian.

Z is the vertical component. At the magnetic poles, the Z component is equal to the total force T and is zero at the magnetic equator. The Z vector directed to the nadir has a (+) sign, and the ***Z*** vector directed to the zenith has a (–) sign.

I - magnetic inclination - the angle composed by the vectors ***T*** and ***H***, depending on the magnetic latitude. The magnetic inclination ***I*** varies within +90 ÷ –90°. Magnetic inclination is identified with the concept of "magnetic latitude", which is also denoted by the letter ***I***.

d - magnetic variation - the angle formed by the true and magnetic meridians. At different points on the earth's surface, the variation is not the same and can take values from 0° to ±180°. If the magnetic needle is deviated from the true meridian to the East, then the variation is considered positive, and if to the west, then negative.

The secular course of declination «d» is indicated on navigation charts.

5.2 Ship's magnetic field

Even during its construction, the ship as a whole acquired a certain magnetization. In navigation, the ship is constantly affected by the Earth's magnetic field, magnetizing (or demagnetizing) the ship's hull, its superstructures and mechanisms. As a result, the ship's iron forms a ship's magnetic field, which distorts the Earth's field. Therefore, the compass card on the ship indicates not the magnetic, but the compass meridian.

The angle formed by the compass and magnetic meridians is called the deviation «δ» of the magnetic compass.

Let's imagine a ship as a material object in the form of a set of uniformly magnetized rectangular elongated bars located along fore-and-aft line, transversely and vertically; rectangular bars represent separately magnetically hard and soft ship's iron (hereinafter - just hard and soft iron). Soft iron is easily remagnetized, while hard iron stably retains its magnetization. In addition, we assume that the Earth's magnetic field in the volume occupied by the ship and the ship's magnetic field near the compass card are uniform fields.

Let us determine the projections X, Y, Z of the intensity vector T of the Earth's magnetic field on the corresponding ship axes x, y, z (Fig. 5.4):

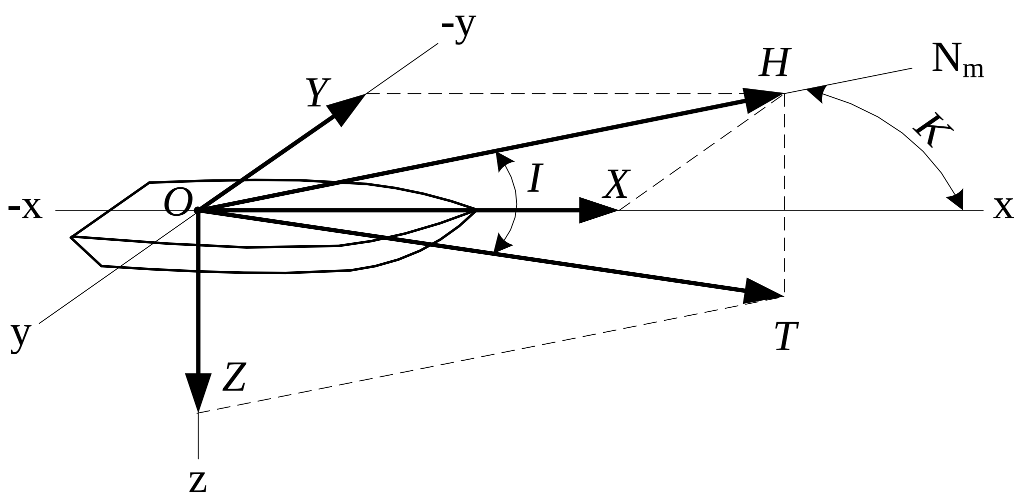


Fig. 5.4. Projections of the vector T on the coordinate axes of the ship

$X = H \cos K = T \cos I \cos K;$

$Y = -H \sin K = -T \cos I \sin K;$

$Z = T \sin I.$

It follows from the obtained equations that the fore-and-aft ***(X)*** and transverse ***(Y)*** components of the Earth's magnetic field strength depend both on the course ***(K)*** and on the magnetic latitude ***(I)***, and the vertical (***Z***) component depends only on the magnetic latitude.

Let us analyze the strength of the magnetic field created by the soft ship iron and determine their projections in the accepted coordinate system [2]. Wherein it is important to keep in mind that the magnetic field of each bar, regardless of its position, has three components - longitudinal, transverse and vertical

When component X acts on the vessel, all longitudinal bars are magnetized and a magnetic field is created around the vessel. The resulting field created by the longitudinal bars consist of three components along the ship's axes

Similarly, the Y component of terrestrial magnetism magnetizes all transverse bars of soft marine iron. The field strength vector can also be decomposed along the ship's axes into three components.

And, finally, the vertical bars of ship's iron are magnetized by the Z component of terrestrial magnetism - we get three components of the field along the ship's axes: longitudinal, transverse and vertical.

Therefore, each of the ship’s soft iron bar creates three components of the magnetic field. The resulting field created by the soft ship iron has nine components. The values and signs of these components on each ship are different.

The permanent magnetic field of the vessel is determined by its intensity along the coordinate axes: longitudinal P, transverse Q and vertical R. The forces P, Q and R can be relatively large depending on the magnitude of the residual magnetism of hard iron. They change in case of moving the iron masses on the ship relative to the compass or moving the compass itself to another place.

5.3. Magnetic compass deviation

Poisson equations. Above it was established that the magnetic compass is affected by the Earth's magnetic field, an alternating magnetic field created by soft ship iron and a permanent field created by hard iron. The analysis of this action made it possible to determine the components of the strengths of the indicated magnetic fields along the ship's axes.

To determine the total magnetic field, it is necessary to algebraically add up all the considered projections of intensities along the corresponding ship axes. As a result, we have: (5.1)

$$\left.\begin{aligned} X' &= X + aX + bY + cZ + P; \\ Y' &= Y + dX + eY + fZ + Q; \\ Z' &= Z + gX + hY + kZ + R. \end{aligned}\right\} \qquad (5.1)$$

Expressions (5.1) are called Poisson's equations, since they were first derived by him on the basis of the hypothesis of uniform magnetization of bodies. The quantities ***a, b, c,…,k*** included in the equations are called Poisson parameters.

In the theory of deviation, the terms that make up Poisson's equations are usually called not intensities, but forces; in the future, we will also use this name.

If the center of the compass card installed on the ship is at point O, then the following magnetic forces will act on the card:

If the center of the compass card installed on the ship is at point O, then the following magnetic forces will act on the card:

X, Y и Z – Earth magnetism forces;

aX, bY,…, kZ – forces created by soft ship's iron;

P, Q и R – forces created by hard ship's iron.

Forces ***X, Y*** and ***Z*** don't depend on the compass location. The forces ***aX, bY, ..., kZ, P, Q and R,*** originating from the ship's magnetism, depend on the location of the compass on the ship and, therefore, have different values for different compasses.

On fig. 5.5, all the forces included in the Poisson equations are graphically shown.

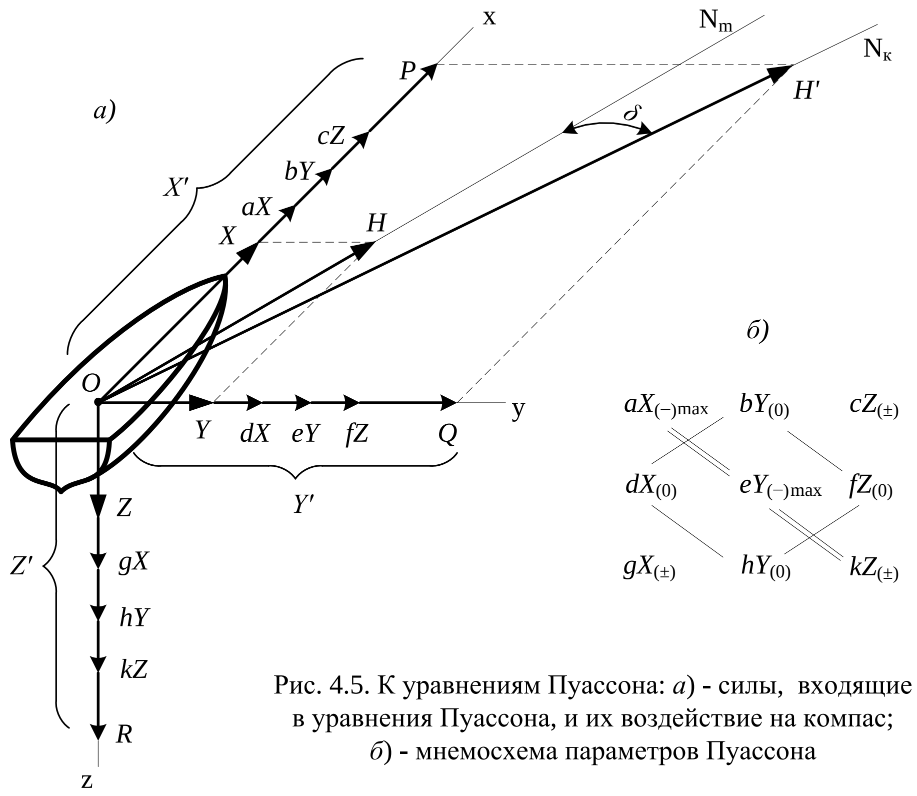


Рис. 4.5. К уравнениям Пуассона: *а*) - силы, входящие в уравнения Пуассона, и их воздействие на компас; *б*) - мнемосхема параметров Пуассона

Ship magnetic forces. It was found that the deviation of a magnetic compass is determined by the action of a number of forces (magnetic field strengths) that have a well-defined magnitude and direction. This problem in relation to the theory of deviation works was solved by the English scientist Archibald Smith [11].

Six such forces have been identified: λH, A'λH, B'λH, C'λH, D'λH, and E'λH. They are called ship magnetic forces.

Parameters ***A', B', C', D'*** and ***E'*** are called exact deviation coefficients, they characterize the magnitude of magnetic forces and are related to the Poisson parameters by the following relations:

$$A' = \frac{d-b}{2\lambda}; \quad B' = \frac{cZ+P}{\lambda H}; \quad C' = \frac{fZ+Q}{\lambda H}; \quad D' = \frac{a-e}{2\lambda}; \quad E' = \frac{a+b}{2\lambda}. \qquad (5.2)$$

The coefficient λ = 1+(a + e)/2 characterizes the decrease in the horizontal component of terrestrial magnetism ***H*** under the influence of soft marine iron. Since the parameters ***a*** and ***e*** are always negative, the coefficient ***λ*** on ships is always less than 1 (one). On the upper bridge it is 0.8 - 0.9, in the wheelhouse - 0.6 - 0.8.

The forces ***A'λH, D'λH*** and **E'λH** are caused by the action of soft iron and change in value depending on the change in the horizontal component of the force ***H*** of the Earth's magnetic field.

Forces ***B'λH*** and ***C'λH*** are caused mainly by hard iron and only partially by soft iron. Their change occurs depending on the change in the vertical component of the Earth's magnetic field ***Z***.

Let us determine in which directions each of the ship's magnetic forces acts.

λH. The force ***λH*** is a guiding force, tending to set the compass card along the magnetic meridian always in the direction of ***Nm***, and does not create a deviation itself.

A'λH. This force is always directed perpendicular to the magnetic meridian, those, directly causes a deviation, but is small in its value.

B'λH. The force ***B'λH*** acts relative to the magnetic meridian at an angle equal to the ship's magnetic course ***K***, i.e. directed along the fore-and-aft line of the vessel. Created mainly by hard iron, and is subject to elimination.

C'λH. Force ***C'λH*** is always perpendicular to the fore-and-aft line of the vessel (force ***B'λH***) and makes an angle with the magnetic meridian equal to (***K*** + 90°) – the force acts on board. It is generated mainly by hard iron, and is subject to elimination.

D'λH. The force ***D'λH*** forms with the magnetic meridian an angle of ***2K*** equal to double ship's magnetic course. Arises from the influence of soft iron, relatively large.

E'λH. The force ***E'λH*** is shifted relative to the force ***D'λH*** by 90°, i.e. directed relative to the magnetic meridian at an angle of (2***K*** + 90°). Arises from the action of soft iron, it is not large.

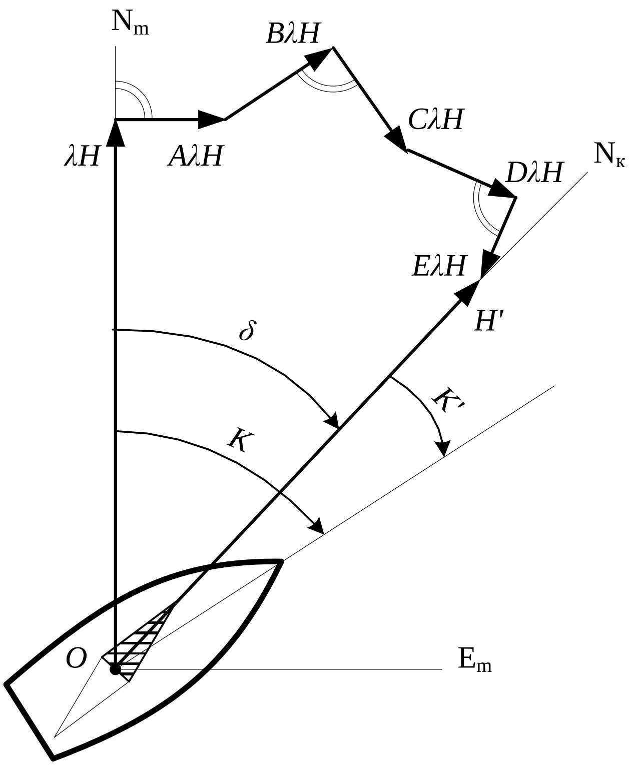


Fig 5.6. Polygon of ship's magnetic forces

According to the rules of geometric addition of vectors, it is possible to construct ***a polygon of the ship's magnetic forces*** for a given course (Fig. 5.6). The closing line of this polygon is the resultant vector ***H′***, which determines the direction of the compass meridian ***Nk*** and clearly shows the formation of the deviation ***δ***.

The compass course ***K′*** is always considered clockwise from the compass meridian, so we will assign a plus sign to it. Deviation ***δ*** is usually counted from the magnetic meridian to the east or west. On fig. 5.6 deviation is positive, i.e. «East».

The basic formula of deviation. The nature of deviations.

The transformation of the Poisson equations makes it possible to obtain the exact formula for the tangent of deviation or the Archibald Smith formula [11] depending on the exact values of the deviation coefficients and magnetic courses. However, its application in practice is impractical, since an elimination of a deviation is carried out regularly and the residual deviation is estimated, the value of which is insignificant. Therefore, when performing deviation work, an approximate formula is used. With a deviation value of up to 6° with sufficient accuracy for practice, the deviation formula after simplifications has the form:

$$\delta = A + B \sin K' + C \cos K' + D \sin 2K' + E \cos 2K'. \qquad (5.3)$$

Simplifications have been achieved by taking into account the fact that magnetic and compass courses are related by the equality: $K = K' + \delta$ and the assumptions: the sine and tangent of a small angle are numerically equal to the angle itself.

As a result, the exact deviation coefficients ***A', B', C', D'*** and ***E'*** are replaced by the values ***A, B, C, D*** and ***E***, referred to as approximate deviation coefficients, which can be determined from observations when evaluating the residual deviation. The resulting formula (5.3) is called ***the basic formula of deviation*** as function of the compass course.

On fig. 5.7 the graphs of the deviations, caused by the corresponding forces depending on the course are shown. The forces are as follows: constant - ***A'λH***; semicircular - ***B'λH*** and ***C'λH***; quadrantal (intercardinal) - ***D'λH*** and ***E'λH.***

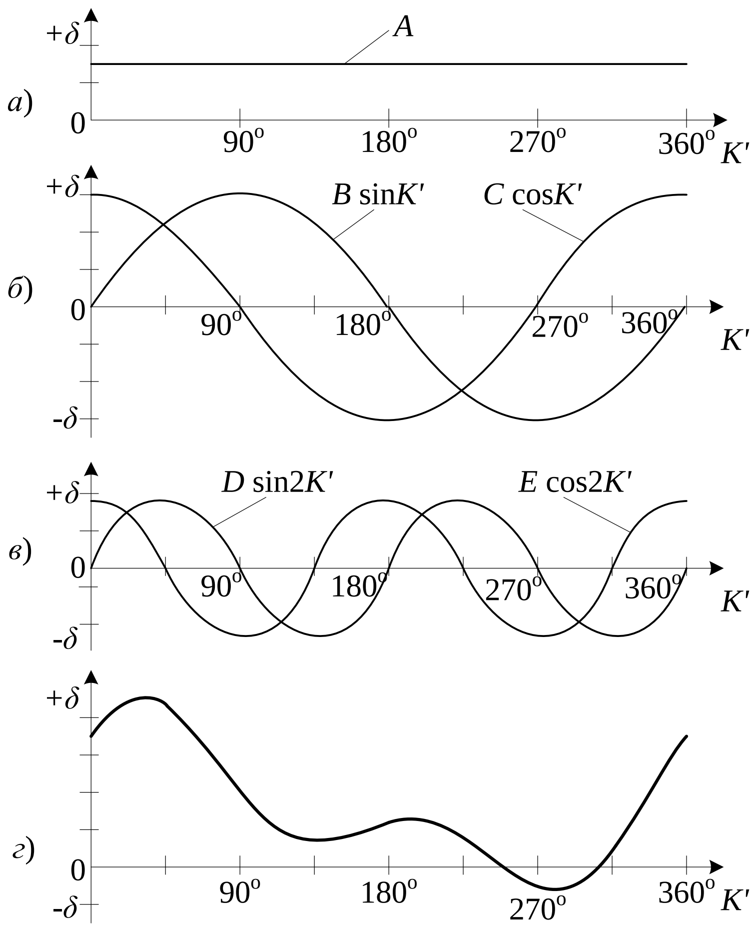


Fig. 5.7. Graphs of a residual deviations:
а) – constant; *б*) – semicircular; *в*) – quadrantal; *г*) – resultant

Thus, the ***δ*** value is equal to the algebraic sum of the constant, semicircular and quadrantal deviations for each compass course. A typical graph of resultant curve is shown in Fig. 5.7, d. This graph is constructed using the basic deviation formula (5.3) and characterizes the residual deviation of the compass after performing deviation work.

5.4. Elimination of magnetic compass deviations

Determination of deviation. Deviation is a variable, the value of which depends on both the course of the ship and the magnetic latitude. Magnetic properties of the cargo also put its influence. The combination of these factors can create a significant deviation which makes unreliable the magnetic compass operation. Inevitably, the question arises of eliminating the deviation and compiling a new table of residual deviation.

Deviation work is carried out, as a rule, at least once a year. The residual deviation of the main magnetic compass should not exceed 3°, and of the steering compass - 5° [10]. The master may extend the validity of the deviation table if the deviation values during control determinations differ from those in the table by no more than 2°. One way or another, the determination of the deviation of the magnetic compass is an integral part of the current work of the navigator and the general complex of deviation work.

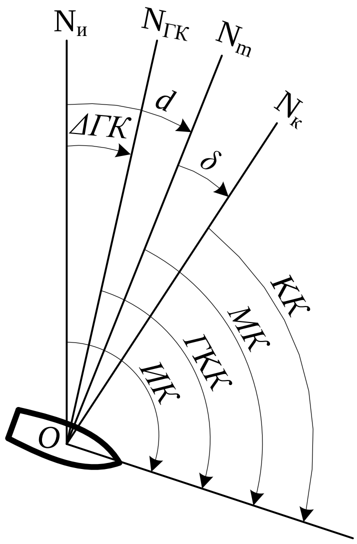


Fig. 5.8. Determination of deviation

In practice, deviation is determined by one of the following main methods:

.- by comparing courses with gyrocompass readings
- on alignment;
- by a distant landmark;
- by celestial bodies;
- for steering compass:
- by comparing courses with the readings of the main magnetic compass.

The most accessible way is to determine the deviation according to the readings of the gyrocompass. Knowing the correction of the gyrocompass ΔGK and the magnetic variation d, the deviation of the magnetic compass δ on a given course is found using known relationships that are easily determined from Fig 5.8.

$$\boldsymbol{ИК = ГКК + \Delta ГК}; \quad \boldsymbol{МК = ИК - d};$$

$$\boldsymbol{\delta = МК - КК} \quad \text{or} \quad \boldsymbol{\delta = ГКК - КК + (\Delta ГК - d)}.$$

The accuracy of determining the deviation in this way depends on the stability of the gyrocompass correction. As is known, when maneuvering a ship, especially at high latitudes at high speed, the gyrocompass has an inertial error, variable in magnitude, slowly decreasing (within several hours after the completion of maneuvering). To minimize these changes in the gyrocompass readings, it is necessary to maneuver at low speed during deviation work and avoid turning the vessel by a large angle.

Elimination of semicircular deviation. To eliminate the semicircular deviation, the Airy method is used, named after the English astronomer D. B. Airy (1801 - 1892). The method is the most common and accurate, it is performed without any auxiliary devices and allows simultaneously eliminate the semicircular deviation on all compasses installed on the ship.

Erie's method consists of four steps

Each step involves setting the ship to one of the main courses ***Nm, Em, Sm*** or ***Wm*** and correcting the observed deviation with help of permanent magnets. Setting the ship to the desired magnetic course can be performed, for example, according to the readings of the gyrocompass. The vessel is stabilized on such a course according to the gyrocompass, which corresponds to the given magnetic one. The value of the ΓКК is calculated by the formula:

$$\boldsymbol{\Gamma KK = MK + d - \Delta\Gamma K},$$

where the magnetic course of the MK takes fixed values of 0, 90, 180 and 270°.

The semicircular deviation created by the forces $\boldsymbol{B'\lambda H}$ and $\boldsymbol{C'\lambda H}$ is determined by the predominant action of the permanent components ***P*** and ***Q*** from the ship's hard iron. Therefore, the elimination of this deviation is carried out by permanent magnets-eliminators made of hard iron. They are installed in the deviation device under the compass bowl. To compensate the force $\boldsymbol{B'\lambda H}$, a pair of longitudinal magnets is used, and to compensate the force $\mathbf{C'\lambda H}$, a pair of magnets located transversely is used.

To clarify the essence of the Airy method, we plot the graphs of the ship's magnetic forces location on the main courses. Preliminary we compile a table of the ship's magnetic forces directions relative to the magnetic meridian ***Nm***, assuming that the deviation coefficients have a positive value:

Km	λH	A'λH	B'λH	C'λH	D'λH	E'λH
0°	0	90	0	90	0	90
90°	0	90	90	180	180	270
180°	0	90	180	270	0	90
270°	0	90	270	0	180	270

$C'\lambda H$ force elimination

Step .1. The vessel set on the course N_m. The polygon of the ship's magnetic forces for this case is shown in Fig. 5.9. Forces $\boldsymbol{\lambda H}$, $\boldsymbol{B'\lambda H}$ and $\boldsymbol{D'\lambda H}$ directed along the magnetic meridian, and forces $\boldsymbol{A'\lambda H}$, $\boldsymbol{E'\lambda H}$, $\boldsymbol{C'\lambda H}$ perpendicular to it. The resultant vector H' is directed to the compass meridian N_K, determining the total deviation δ_N, which is observed on the compass card.

With help of a handle «***C***» in the deviation device, turn a pair of transverse compensating magnets so that the deviation $\boldsymbol{\delta N}$ is brought to zero. This means that the compensating magnets created a transverse oppositely directed force:

$$\boldsymbol{F = -(A'\lambda H + E'\lambda H + C'\lambda H)}.$$

It should be noted that the deviation device construction may be different depending on the type of magnetic compass. For example, several individual bar magnets can be used as correcting magnets, which in this case is installed into the intended transversely directed holes.

Step 2. The ship set on the magnetic course ***Sm*** (Fig. 5.9, b). Here, the directions of the forces $\boldsymbol{C'\lambda H}$ and $\boldsymbol{F}$, as well as the force $\boldsymbol{B'\lambda H}$ relative to the meridian, change by 180°. Imagine that the force $\boldsymbol{F}$ is equal to the sum of two forces: $\boldsymbol{F = f_1 + f_2}$. Moreover, the force $\boldsymbol{f_1} = |\boldsymbol{A'\lambda H + E'\lambda H}|$, while the force $\boldsymbol{f_2} = |\boldsymbol{C'\lambda H}|$. Then the force $\boldsymbol{f_2}$ will fully compensate for the force $\boldsymbol{C'\lambda H}$ and the deviation on this course will be determined by the sum of the forces: $\boldsymbol{\delta_S = f_1 + (A'\lambda H + E'\lambda H)}$. Since these forces are equal, by moving the same transverse magnets, the deviation is reduced by half. Usually, the deviation from the sum of forces ($\boldsymbol{A'\lambda H + E'\lambda H}$) is small, and hence it is also small from the force $\boldsymbol{f_1}$. Therefore, the error from replacing the bisector with the median in the triangle of forces will be insignificant. As a result, the magnets will act on the compass only by the difference in forces ($\boldsymbol{F - f_1}$), compensating for the force $\boldsymbol{C'\lambda H}$ on all courses.

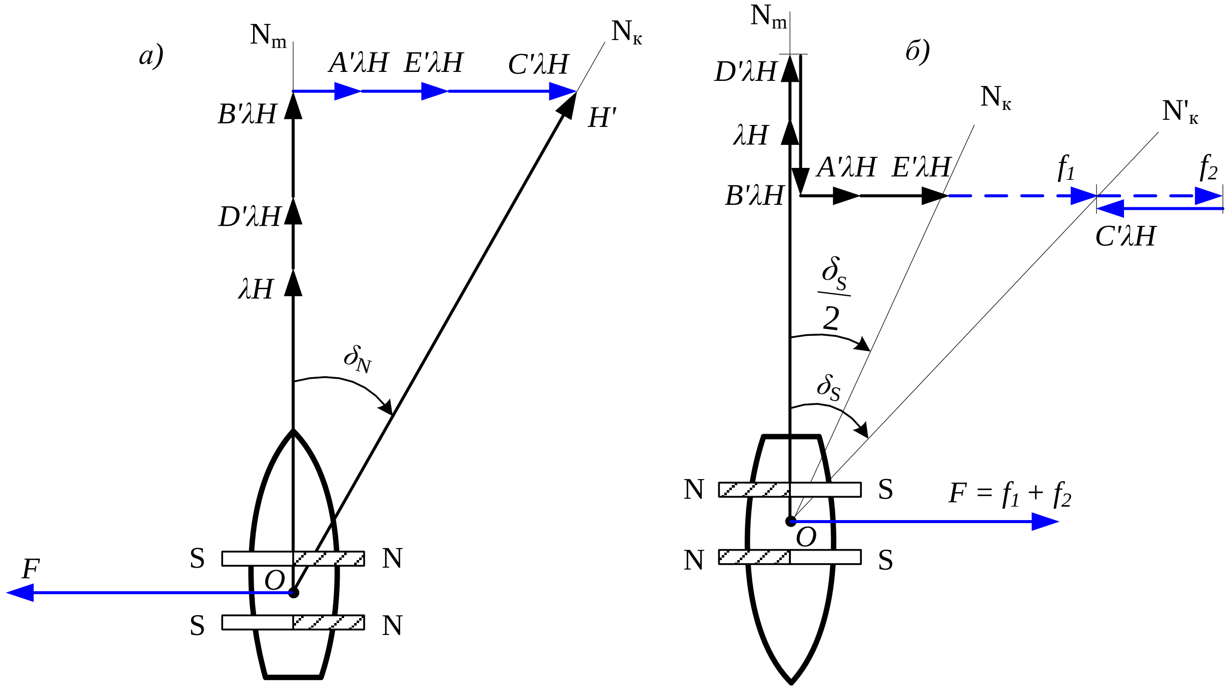


Fig. 5.9. Elimination of semicircular deviation created by athwartship force $C'\lambda H$
a) –ship on course N_m; *б*) – ship on course S_m

The compensation of the longitudinal force $\boldsymbol{B'\lambda H}$ is carried out in a similar way, but they already operate with longitudinal compensating magnets. On the magnetic course ***Em***, the deviation $\boldsymbol{\delta_E}$ is reduced to zero, and on the magnetic course ***Wm***, the observed deviation $\boldsymbol{\delta_W}$ is reduced to its half value.

However, the full semi-circular deviation will not be eliminated as the forces from the ship's soft iron were not compensated. In the future, the exact deviation coefficients ***A', B', C', D'*** and ***E'*** will be replaced by approximate values of ***A, B, C, D*** and ***E***, which will be determined from residual deviation observations.

Elimination of quadrantal deviation. The quadrantal deviation is created by the forces $\boldsymbol{D'\lambda H}$ and $\boldsymbol{E'\lambda}$H and is determined by the action of only soft ship iron. This means that the compensation of these forces must be provided by compensators made of soft ferromagnetic material. The compensation condition can be expressed in terms of the corresponding quadrantal deviation coefficients ***D'***, ***E'*** of the ship's soft iron and ***Dk***, ***Ek*** from the soft iron of the compensator: ***D' = - Dk*** and ***E' = - Ek***.

As compensators, longitudinal bars of round or rectangular cross section or balls are used, installed in the upper part of the binnacle, from the outside, symmetrically at the level of the compass card. The balls are fixed symmetrically at a certain distance from the compass bowl, which is determined during deviation work (see Fig.

Modern magnetic compasses are equipped with non-inductive [3] quadruntal deviation compensators in the form of a set of 16 plates, which are installed in two cases of 8 plates on each side of the compass bowl (Fig. 5.10).

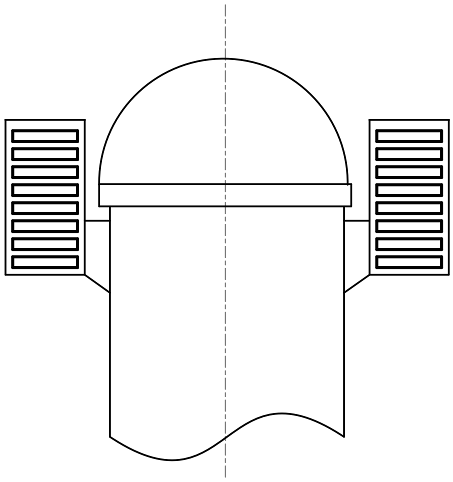


Fig. 5.10. Magnetic compass with set of plates-compensators

Each plate increases the coefficient ***Dk*** by 0.5°. When installing all 16 plates, the total compensation coefficient ***Dk*** reaches the value of 8°. With the help of such a set, it is possible to cause compensation of a quadrantal deviation with a residual coefficient ***D*** of no more than 0.25°.

In most cases the elimination of the quadrantal deviation is limited by compensation for the ***D'λH*** force, since the ***E'λH*** force is very small

Heeling error and its compensation. With a strong rolling, the compass card begins to "walk" to the right and left so that it becomes difficult to read the course. This is due to the influence of the vertical component of the total magnetic field.

The vertical component ***Z*** of the Earth's magnetic field magnetizes all vertical bars of the ship's iron and the ship can be represented as a vertical magnet: the north pole is in the keel area, and the south pole is in the deck area. The resulting force of such a magnet can be determined as a vector ***Fv***. Then, when the ship rolls, in the card plane arises a horizontal component of the vertical magnet $\boldsymbol{F'_{в} = F_{в} \sin\theta}$, that caused deviation (Fig. 5.11, *a*). As a result, the card leaves the compass meridian, determined by the vector ***H'***, at an angle $\boldsymbol{\delta_{кр}}$, called the ***heeling error***.

The deviation of the card is especially noticeable on compass courses N and S, since in these cases the transverse component acts perpendicular to the ship's fore-and-aft line, similar to the action of the transverse force ***CλH*** (Fig. 5.11, b). On the other two main courses - ***E*** and ***W*** - the transverse component coincides with the magnetic axis of the card (Fig. 5.11, c) and therefore does not have a deflecting effect on the compass needles. It becomes clear that $\boldsymbol{\delta_{кр}}$ has a semicircular character, reaching its maximum value at courses 0 and 180° and zero - at courses 90 and 270°.

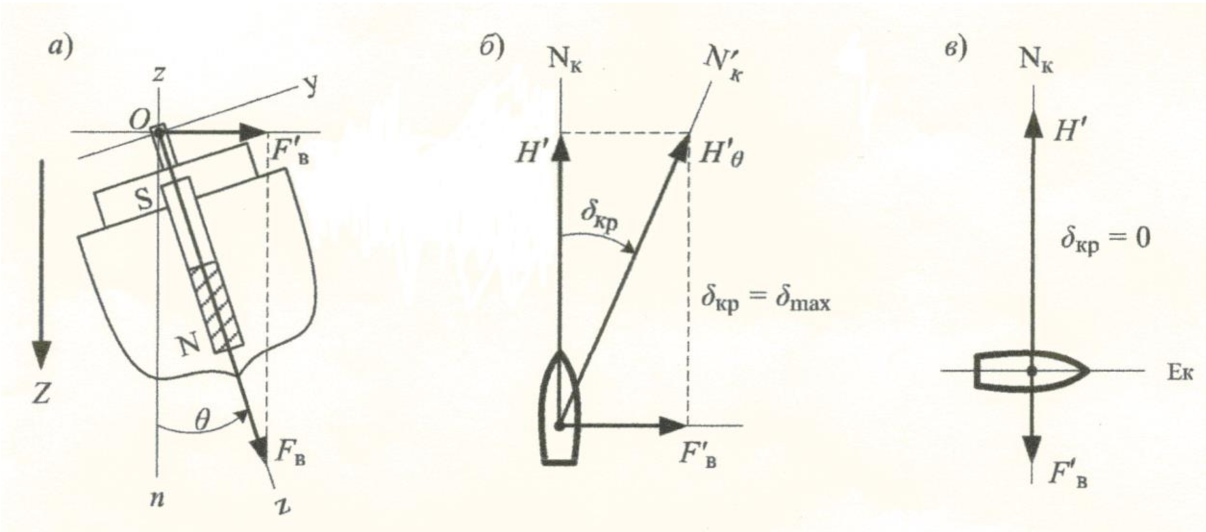


Fig 5.11. Arising a heeling error: a) - appearance of an athwartships force when the ship is tilted; b) heeling error on course ***Nk***; c) heeling error on the course ***Ek.***

To eliminate this phenomenon, it is necessary to create such magnetic conditions for the compass under which the athwartships component ***Y′*** would not change when the vessel tilted. This means that if the force ***Fv*** is compensated, then the periodically appearing additional transverse component ***F'v*** will be absent. Then a vertical compensation magnet can be used for this purpose.

The vertical (heeling) magnet must be installed so that its force compensates for the vertical component R created by the ship's hard iron.

The condition for the compensation of the heeling error is the equality of the magnetic inclination ***I′***, measured in the center of the compass bowl, to the magnetic inclination ***I***, measured ashore.

In practice, the heeling error is compensated using a special device - a ship inclinator [2, 11], which is a highly sensitive magnetic system. To do this, it is necessary (with the compensated force ***C'λH***): lie down on the magnetic course ***E*** or ***W***; remove a bowl from the compass and install the inclinator in its place; measure the ship's magnetic inclination $\boldsymbol{I'_{E,W}}$ and compare it with the Earth's magnetic inclination ***I***, which can be taken from a magnetic map. Further, by moving the vertical heeling magnet up or down, bring the value of $\boldsymbol{I'_{E,W}}$ to the value of ***I*** - the heeling error will be compensated.

Compiling a deviation table. As a rule, during navigation, the semicircular deviation changes, so periodically it becomes necessary to compensate it and compile a new deviation table. The procedure for performing this kind of deviation work consists of several stages.

1. Making a decision on the need to eliminate the semicircular deviation. As noted above, in accordance with the requirements of РШСУ-90, the observed deviation should not differ from the tabular values more than 2°. The deviation of the main magnetic compass should not exceed 3°, and the track compass - 5°.

2. Elimination of semicircular deviation (Airy method). The deviation is eliminated on the main magnetic courses. Here, special attention should be paid to the control of the position of the vessel on these courses.

3. Determination of the residual deviation on the main and quarter compass courses. The measurement result is the residual deviation values $\boldsymbol{\delta_N}$, $\boldsymbol{\delta_{NE}}$, $\boldsymbol{\delta_E}$, $\boldsymbol{\delta_{SE}}$, $\boldsymbol{\delta_S}$, $\boldsymbol{\delta_{SW}}$, $\boldsymbol{\delta_W}$ and $\boldsymbol{\delta_{NW}}$.

4. Calculation of the approximate coefficients of residual deviation ***A, B, C, D*** and ***E*** according to the formulas:

$$A = \frac{1}{8}(\delta_1 + \delta_2 + \delta_3 + \delta_4 + \delta_5 + \delta_6 + \delta_7 + \delta_8);$$

$$B = \frac{1}{4}(\delta_3 - \delta_7 + 0{,}71(\delta_2 + \delta_4 - \delta_6 - \delta_8));$$

$$C = \frac{1}{4}(\delta_1 - \delta_5 + 0{,}71(\delta_2 - \delta_4 - \delta_6 + \delta_8));$$

$$D = \frac{1}{4}(\delta_2 - \delta_4 + \delta_6 - \delta_8); \quad E = \frac{1}{4}(\delta_1 - \delta_3 + \delta_5 - \delta_7),$$

где $\boldsymbol{\delta_1}, \boldsymbol{\delta_2}, \ldots, \boldsymbol{\delta_8}$ – values of residual deviation for the courses: ***N, NE,…, NW.***

5. Calculation of deviation. Based on the obtained approximate deviation coefficients ***A, B, C, D*** and ***E***, using the general deviation formula (6.3), the deviation is calculated by substituting the values of the coefficients and the compass courses into the formula:

The deviation table is compiled for 24 equally spaced (every 15°) or 36 (every 10°) compass courses.

With carefully performed deviation work, the residual deviation usually does not exceed 1 - 2°.

The residual deviation table is an official document, which is drawn up on a form and signed by the deviator or the master. When transporting ferromagnetic cargo, it is allowed to use a temporary deviation table.

When sailing, deviation changes are monitored and, if necessary, adjustments can be made to the current deviation table. Since the semicircular deviation changes to the greatest extent, then, observing the deviation on the four main magnetic courses, new values of the semicircular coefficients are calculated using the formulas:

$$B = \frac{(\delta_{\mathrm{E}} - \delta_{\mathrm{W}})}{2}; \quad C = \frac{(\delta_{\mathrm{N}} - \delta_{\mathrm{S}})}{2}.$$

According to the new values of the coefficients ***B*** and ***C*** and the previous values of the coefficients ***A***, ***D*** and ***E***, a more accurate new deviation table is compiled.

Improving the accuracy of the magnetic compass. In order for the forces of semicircular deviation ***B'λH = cZ + P*** and ***C'λH = fZ + Q*** to maintain their stability when the vessel moves from one area to another, it is necessary to compensate for each force not with one compensator, but with two: forces ***cZ*** and ***fZ*** with vertical bars soft iron, and the forces ***P*** and ***Q*** – fore-and-aft and athwartships magnets.

For this purpose, two identical vertical rods are used, installed in mutually perpendicular planes on the binnacle symmetrically: to the right and left of the diametral plane at an angle of 45°. The design is called a latitude compensator or flindersbar - it is shown in fig. 5.12 in the KM-145 compass (Russia) and in the Reflecta-1 magnetic compass (Germany) in the form of a single rod (Fig. 5.13) [4].

Fig. 5.12. Magnetic compass KM-145

Fig. 5.13. Magnetic compass Reflecta -1

6. BASIC CONCEPTS OF HYDRO-ACOUSTIC

6.1. An acoustic waves propagation in water

The physical nature of sound. The operation of hydro-acoustic navigation instruments is based on the emission of acoustic energy into the aquatic environment, the reception and processing of echo signals resulting from reflection or scattering from water objects [2, 3].

Sound as a physical process is a special case of mechanical oscillatory motion of a material elastic medium. The sound source can be, for example, a mechanical oscillatory system placed in a liquid. The oscillating surface of the sound source periodically causes compression and expansion of the adjacent layer of particles of the aquatic environment, which in turn transmit this perturbation to neighboring particles, etc. Particles of the medium are miniature oscillatory systems interconnected by elastic forces. Areas of condensation and rarefaction are formed, which successively move away from the source of oscillations. This wave process of periodic oscillations is called sound propagation.

Fluid particles are not carried away by the acoustic wave, but only transmit perturbation to neighboring particles. The perturbation transmission speed from particle to particle is called the speed of sound c.

The wave front is some imaginary surface, all points of which oscillate with the same phase. Lines normal to the wave front, coinciding with the direction of its propagation, are called sound rays.

Sound waves in real conditions have a complex shape. Waves of the simplest forms include flat, spherical and cylindrical, depending on the shape of the surface of the oscillation source. Depending on the oscillation frequency, waves are divided into infrasonic (less than 16 Hz), sound (16 - 20,000 Hz) and ultrasonic (more than 20 kHz).

A harmonic sound wave is characterized by:

- a wavelength λ - the distance between two maxima or minima of the perturbation;

- a period T - the time during which one oscillation cycle is completed.

They are related by the ratio: $\lambda / c = T$.

Instead of a period ***T***, frequency ***f*** is often used, equal to the number of periods per time unit: $f = 1/T$, then $f \lambda = c$.

Under certain conditions, geometric acoustics makes it possible to neglect the wave nature of sound and, instead of a wave, consider the movement of its front or an elementary section of the latter along the sound beam. The main provisions of this method were developed by the Dutch physicist H. Huygens (1629 - 1695), formulating it in a well-known principle: ***at any time, the particles that make up the wave front are sources of elementary spherical waves; the envelope of these waves determines the new position of the wave front.***

The speed of sound in the sea. In an ideal medium, the speed of propagation of acoustic waves is determined only by its physical properties. The propagation velocity of an acoustic wave can be expressed in terms of the bulk modulus [2, 3]:

$$c = \sqrt{\frac{k}{\rho}} \ ,$$

where ***k*** is the modulus of bulk elasticity;

ρ is the density of water.

The values of ***k*** and ρ depend on temperature, water salinity and hydrostatic pressure (depth), so the speed of sound is also a function of these factors.

With an increase in temperature by 1°C, the speed of acoustic waves increases by ~ 4 m/s in cold water (up to 10°C) and by 2.5 m/s in warm water (25–30°C).

An increase in depth per meter in the upper layer (0 - 100 m) leads to an increase in the speed of acoustic waves by 0.0164 m/s, and near the bottom (~5000 m) - by 0.0183 m/s.

The change in salinity has little effect on the speed of acoustic waves, since it is small in itself. Thus, with an increase in salinity by 1‰ (per mille), the speed of acoustic waves increases by 1 m/s.

With an increase in depth of 10 m, the static pressure increases by approximately 10^5 Pa.

On average, the speed of sound in the sea can vary between 1440 - 1580 m/s.

To determine the speed of propagation of acoustic waves, empirical formulas are used, one of them, called the Wilson's formula, which is given below:

$$\mathbf{c = c_o + \Delta c + \Delta c_h,}$$

where c_o = 1449.14 m/s is called the reference speed of sound calculated for temperature t = 0°C, salinity S = 35‰ and pressure 1.033 kg/cm^2 (one atmosphere);

$\Delta c = \Delta ct + \Delta cs + \Delta c_{hst}$ is the sum of corrections for temperature, salinity and interaction of depth (pressure), salinity and temperature, respectively, tabulated by depth ranges;

Δc_h is the correction for depth ***h***.

Corrections are given in the Nautical Tables.

Reflection and refraction of acoustic waves. The most important acoustic characteristic of a medium is its acoustic resistance, which is equal to the product of the density of the medium ρ and the speed of sound c in it.

When a sound wave falls on the interface between two media having different acoustic resistance (for example, $\rho_1 c_1$ and $\rho_2 c_2$), ***part of the sound energy is reflected at the same angle at which the fall occurs, and the rest, refracted, penetrates into the adjacent medium.***

In the general case, we can draw conclusions: when the acoustic resistances of the media differ slightly, then one part of the sound energy is reflected, and the other goes into the second medium; if $\rho_1 c_1 >> \rho_2 c_2$ or $\rho_2 c_2 >> \rho_1 c_1$, then all the incident energy is reflected into the first medium; when the acoustic resistances are equal ($\rho_1 c_1 = \rho_2 c_2$), the sound energy is completely transferred from the first medium to the second one.

Diffraction of sound waves. ***Sound waves in the process of propagation have the ability to bend around obstacles encountered on the way. This phenomenon is called sound diffraction.*** The degree of diffraction depends on the ratio of the size of the obstacle d and the wavelength λ:

$d >> \lambda$ - the incident acoustic wave is completely (partially) reflected from the interface between two media, an “acoustic shadow” zone is formed behind the barrier, there is no (insignificant) diffraction;

$d \approx \lambda$ – the “acoustic shadow” zone disappears; diffraction manifests itself quite strongly;

$d << \lambda$ – the acoustic field is practically not disturbed.

When locating underwater objects with the help of a sonar, high-frequency acoustic vibrations are usually used to make it possible to detect objects of small size.

Refraction of sound rays. The thickness of sea water can be represented as consisting of separate horizontal layers of infinitely small thickness, in each of which the density of water and the speed of sound are constant. A sound beam propagating in such a layered medium, passing from layer to layer, will experience reflection and refraction, which leads to its curvature and scattering of part of the sound energy.

The phenomenon of the curvature of sound rays due to the inhomogeneity of sea water is called sound refraction. The refraction of sound can have a great influence on the results of measurements of distances and angles using hydroacoustic instruments.

Interference of sound waves. If not one, but several waves propagate in the medium, then each particle of the medium performs the resulting oscillatory motion. The resulting displacement of the particles of the medium at any time is the geometric sum of the displacements caused by each of the emerging oscillatory processes separately.

As a result of the addition of several wave processes, at some points of the acoustic field, amplification may occur, and at others, weakening of the oscillations. This process is called the interference of sound oscillations.

Interference conditions: a) same or multiple frequency; b) the same direction of particle displacement; c) the constancy of the phase difference. Sources of fluctuations that satisfy these conditions are called coherent.

Reverberation. When sound propagates, multiple reflections from many sound diffusers are possible. The resulting interference pattern of numerous very weak reflections from small bodies and inhomogeneities is perceived as an oscillating damped echo after the end of the signal transmission. ***This phenomenon, which is a certain type of interference, is called reverberation.*** Reverberation significantly affects the operation of active sonar.

Attenuation of acoustic waves. The intensity of acoustic waves decreases as the distance from the source increases. First of all, this is due to the expansion of the area of the wave surface with increasing distance - more and more particles are involved in the process, which leads to a decrease in the amplitude of their oscillations. The presence of internal friction (viscosity) and thermal conductivity in water causes an irreversible transition of sound energy into heat.

When a sound wave is attenuated due to scattering and absorption, the formula is used to determine the sound intensity at a distance $\boldsymbol{x}$ from the source

$$\boldsymbol{I = I_o\, e^{-\beta x}},$$

where: - $\boldsymbol{I_o}$ is the sound intensity on the surface of the oscillation source;

- $\boldsymbol{\beta}$ is the attenuation factor (in dB/km).

Experimental studies show that the spatial attenuation of sound waves in the sea is close to a quadratic dependence on the frequency $\boldsymbol{f}$ of the sound wave, i.e. the higher the frequency of the sound signal, the more it is absorbed by the medium. This factor is limiting in the operation of hydro-acoustic devices.

Empirical formulas are used to determine the attenuation coefficient. For example, for estimated calculations that do not require high accuracy, in the frequency range $\boldsymbol{f}$ from 5 to 60 kHz, you can use the formula [2]:

$$\boldsymbol{\beta = 0{,}036\, f^{3/2}}.$$

6.2. Hydroacoustic antennas

The emission and reception of acoustic oscillations in hydroacoustic devices is carried out by acoustic antennas. The main elements of the antennas are electro-acoustic transducers (vibrators), which have the ability to convert electrical energy into mechanical energy and vice versa. In the transmitting antenna, electrical impulses from a special generator are converted into an oscillatory movement of its radiating surface, which is transmitted to the aquatic environment. In the receiving antenna, the receiving surface, under the influence of the reflected acoustic wave, performs mechanical vibrations, which are converted into an electrical signal.

In modern hydroacoustic instruments, piezoelectric antennas are mainly used.

Piezoelectric substances, in particular piezoceramics, have the property that when deformed under the action of external mechanical pressure, electric charges arise on their surfaces. This effect is called the direct piezoelectric effect and was discovered in 1880 by the brothers Pierre and Jacques Curie.

The inverse piezoelectric effect was soon confirmed, namely, that such a substance located between two electrodes reacts to an electrical voltage applied to it by changing its shape. The first effect is currently used for measurements, and the second - for the excitation of mechanical pressures, deformations and vibrations.

The main natural piezomaterials are quartz and tourmaline, but crystals (chemical derivatives) of barium titanate $BaTiO_3$ and piezoelectric structures based on it have the greatest practical value.

Piezoelectric transducers are small in size and weight, have high sensitivity and the ability to operate at high frequencies.

An oscillatory system of vibrators-emitters of ultrasonic energy is assembled from a plurality of identical piezoelectric prisms fixed at one end to a steel membrane. The surfaces of the prisms are sprayed with silver electrodes, which are connected to an alternating current source. Due to the reverse piezoelectric effect, alternating current causes longitudinal oscillations of prisms. They are transferred to the membrane and through the insulator in contact with it, to the water. The moment of arrival of the reflected sound wave is recorded as the occurrence of an electrical signal received from the vibrator - a direct piezoelectric effect.

Depending on the purpose, a variety of converter designs are used. The geometric dimensions of the piezoelectric element are determined by the frequency of oscillations used in the study. Currently, converters for frequencies of 25 kHz - 5 MHz are widely used.

6.3. Directional properties of hydroacoustic antennas

Hydroacoustic emitters and receivers have the property of directionality. This property is manifested in the fact that the emitter concentrates energy in a certain solid angle, and the output signal of the receiver depends on the direction to the source. As a result, the intensity of radiation increases, it becomes possible to determine the direction to the object.

Let us consider the physical essence of the directed action of the vibrator-emitter.

On the radiating line of a flat radiator, we select two points A and B, located symmetrically with respect to the center O at a distance of l/2 (Fig. 6.1, a).

These points oscillate in phase and synchronously and, in accordance with the Huygens principle, are independent sources of spherical waves, like any other points of the radiating surface. That is, in our case, each point of the vibrator sends vibrations to the surrounding space in all directions.

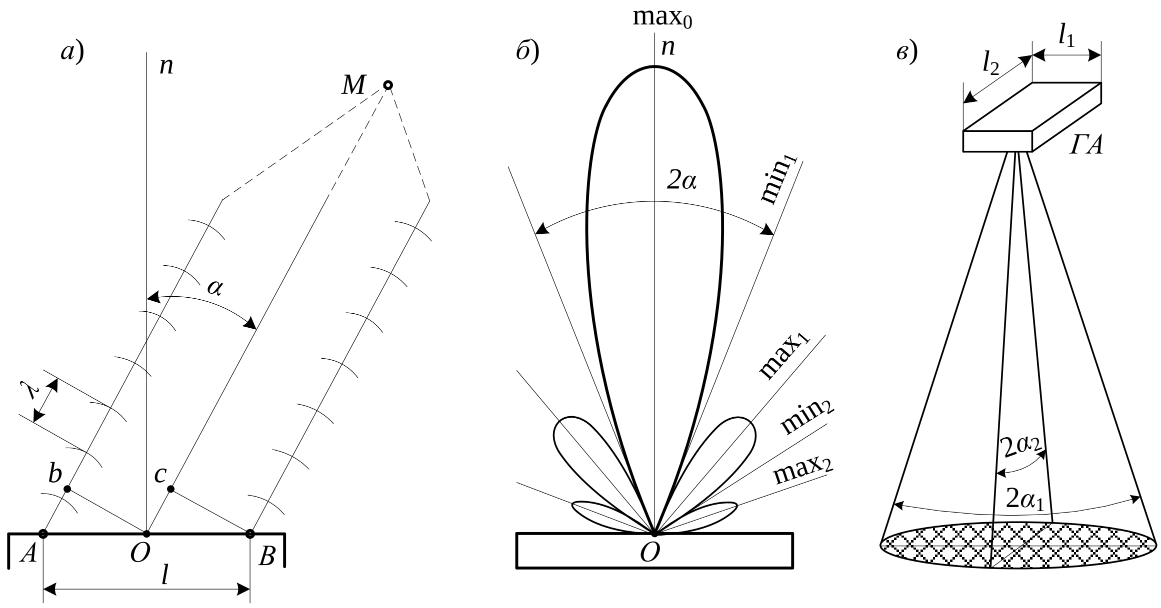


Fig. 6.1. Directionality of hydroacoustic antennas
a) - interference of acoustic waves of the emitter; b) - polar radiation pattern of the emitter; c) - the main maximum of the antenna pattern.

However, two identical in-phase emitters A and B with a base between them $\boldsymbol{l}$ greater than the wavelength $\boldsymbol{\lambda}$, create radiation due to interference in which the amplitude of oscillations (velocities, pressures, power) will depend on the direction $\boldsymbol{\alpha}$ to the normal ***nO***.

If the studied point of the sound field M is placed on the normal nO, then the sound rays will arrive at it with the same phase, i.e. the phase shift is zero. The resulting sound pressure amplitude will be maximum. Therefore, at points lying on the axis of the emitter ($\boldsymbol{\alpha = 0}$), there is a maximum of sound pressure. This direction is called ***the main maximum.***

With further deviation from the normal, the difference in the path of the rays increases, and the amplitude of the sound pressure decreases. As soon as the oscillations are in antiphase ($\boldsymbol{\psi = \pi}$, which corresponds to a difference in the path of the rays equal to 0.5λ), the resulting amplitude vanishes.

Angles $\boldsymbol{\alpha_{max}}$ and $\boldsymbol{\alpha_{min}}$, (Fig. 6.1, b) correspond to the max. amplitude of pressure under the condition $\boldsymbol{\psi = 0}$ (even number 2kπ) and the min. amplitude of pressure under the condition $\boldsymbol{\psi = \pi}$ - an odd number $\boldsymbol{(2k + 1)\pi}$. Here ***k*** takes the values 0, 1, 2, …

In addition to the main maximum (k = 0, αmax0 = 0), there may be several more lateral radiation maxima when the difference in the path of the rays reaches an integer value λ. Similarly, after the first minimum (k = 0, sin αmin = λ/2l), subsequent minima are possible when the difference in the path of the rays is a multiple of λ/2 - these are the directions of zero intensity.

Thus, the energy of the ultrasonic wave is mainly distributed within the directivity angle 2α, corresponding to the angles of the minimum amplitude of the sound pressure sinαmin1. The distribution of acoustic energy within the angle 2sinα = λ / 2l determines the directivity characteristic of the emitter, which is graphically depicted as a diagram in the polar coordinate system (Fig. 6.1, b).

The direction of action of the vibrator depends on the ratio between the length of the emitted wave λ and the linear dimensions of the vibrator l, the working surface of which is a plane. By adjusting these parameters it is possible to concentrate the sound energy within the desired solid angle. The number of lateral maxima and minima is also determined by the ratio between the wavelength λ and the dimensions of the vibrator l.

Let us give an example of the directional action of a conditional rectangular hydro-acoustic antenna (Fig.6.1, c).

Initial data: s = 1500 m s^{-1}; f = 50,000 Hz. Dimensions of the area of the radiating surface of the antenna: $\boldsymbol{l_1}$ = 0.05 m; $\boldsymbol{l_2}$ = 0.15 m.

Let's calculate the wavelength: $\boldsymbol{\lambda = c/f}$ = 0.03 m.

The angle along which the minimum of sound energy is observed in the direction l_1: $\sin\alpha_{min1} = \lambda/2l_1 = 0.03/0.1 = 0.3$; $\alpha_{min1} = 17.5°$. Then $2\alpha_{min1} = 2\alpha_1 = 35°$.

In the direction l_2 we get: $\sin\alpha_{min1} = 0.03/0.3 = 0.1$; $2\alpha_2 = 10.4°$.

6.4. Phased array antennas

The improvement of the element base in the construction of hydroacoustic antennas has led to the creation of phased antenna arrays (PAR) - antennas consisting of a group of emitters, the signal phase in which can be controlled independently, forming an effective radiation of the antenna as a whole in one desired direction, different from the direction of effective radiation of a separate element [4].

The basis of the "phased antenna array" system - PAA - is a special ultrasonic transducer with a certain number of individual piezoelectric elements (usually from 16 to 256, but it can be more - it depends on the practical goals of the research). The PAR system sends and receives pulses from numerous array elements. The elements are excited in a certain order so that the components of the beam form a single wave front propagating in a given direction. Similarly, the receiver combines the signals received from the elements into a single representation. Because phased array technology allows electronic beamforming and control, a single transducer is enough to create a large number of different beam profiles.

There are two main types of systems based on phased antenna arrays - passive and active antenna arrays. The main difference is this: in passive antenna arrays there is one powerful transceiver, whose signal is divided into all channels, conditionally containing only a phase rotation element.

In active phased arrays (APA) antenna, the channel of each array element has its own transceiver. They have a huge safety margin - the failure of one transceiver does not lead to a breakdown of the entire system, but at the same time, the complexity of control and the cost of the device as a whole increase significantly. However, the development of a modern base of electronic components, their miniaturization and their mass production make it possible to displace passive arrays from positions that have long been occupied and widely use APA antennas in the sea and fishing fleet, in hydrography and in the study of the World Ocean.

Below, as an example, is shown an active phased arrays antenna developed at “Elpa” OJSC [4].

Fig. 6.2. Active phased arrays hydro-acoustic antenna «Элпа»

The hydroacoustic transducer is designed for electroacoustic conversion of received and emitted signals and formation of specified spatial receiving and emitting characteristics of ultrasonic beams for detecting and locating underwater objects, measuring distance and speed. The operating mode of the converter is pulse. Can be used as an active element of the echo sounder and Doppler log.

The width of the directivity characteristic of an individual beam in the radiation mode at a level of 0.7 is only 3°± 0.3, and with the possibility of scanning within ± 30°.

On the other hand, the total number of active antenna elements is 960 (this can be seen in Fig. 6.2), and the number of elements in each channel is 240. That is, it is possible to independently control the operation of four channels within one antenna. Each channel consists of a number of separate groups of active elements (apertures), phased controlled according to a given program in order to create the resulting beam in this case with a beam width $\boldsymbol{\Delta\theta = 3°}$**.**

Thus, the possibilities of the widest plan for the creation of hydroacoustic antennas are opened up, capable of continuously forming and analyzing acoustic space within the given limits and proportions of angular scanning according to a given program.

7. ECHO SOUNDERS

7.1. An echo sounder principle of operation

Hydroacoustic instruments designed to determine the vertical distance to any underwater object are called echo sounders (ES). According to their purpose, ES are divided into the following main varieties:

• Navigational ES designed to ensure the safety of navigation;

• Sounding instruments used for carrying out hydrographic works with high accuracy;

• For seabed mapping (e.g. multibeam);

• Fish-searching;

• Special (on trawls, underwater vehicles, etc.).

The principle of ES operation is based on measuring the time delay between the moments of emission towards the bottom of the probing pulse of acoustic energy and the arrival of the echo signal in the receiving path [2, 3].

Thus, the main task of determining the depth with the help of an echo sounder is practically reduced to measuring a small time interval between the moments of emission and reception of a signal reflected from the sea bottom.

Typical echo sounder functional diagram is presented on fig 7.1. Such echo sounder (for example, НЭЛ М-3Б) [2, 5] are composed of a depth recorder (DR), a digital depth indicator (DDI), and a depth signaling device (DSD) for a signaling of the given depth. Depending on the mode of operation, in one of these devices with a certain frequency, a triggering pulse is formed.

This pulse is the starting point for the further formation of a short series (package) of pulses from the master high-frequency generator in the transmitting-receiving device (TRD). The pulses amplified in the amplifier (AMP) come to the transmitting-receiving antenna (TRA) which emits a probing ultrasonic pulses.

The echo signal reflected from the ground is converted in the TRA into an electrical signal. After amplification and noise filtering in the AMP and TRD, the signal is sent to the corresponding instruments to indicate the depth.

$\boldsymbol{C_o}$ = 1500 m/s is taken as the calculated speed of sound in water. Knowing the total time $\boldsymbol{t}$ of signal propagation to the seabed and in opposite directions, it is easy to determine the depth $\boldsymbol{h}$ under the keel of the ship:

$$h = (c_o \times t)/2.$$

The functional scheme of modern echo sounders has remained the same - determining the depth under the keel of the vessel with maximum accuracy, taking into account the real situation: current navigation conditions and the bottom surface of the sea.

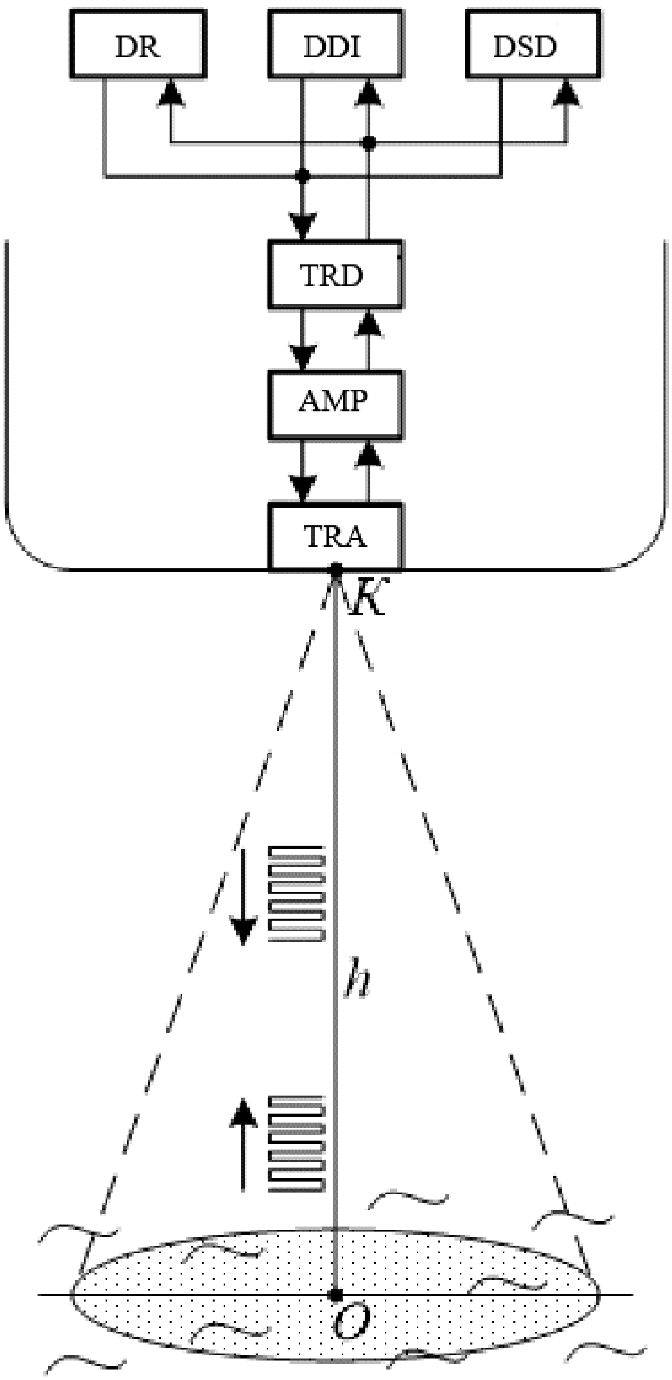


Fig. 7.1 Echo sounder functional diagram

The hydro-acoustic antenna is a piezoelectric system with a fixed or controlled setting, sometimes combined with the hydro-acoustic antenna of a ship's log.

The reflected echo signal is also analyzed in the transceiver and comes in the form of not only a digital reading of the current depth, but is also presented on color indicators for displaying the bottom topography at the moment and for some previous time interval.

Storage the information about the passage depths on paper is practically not used today - all current information in digital form entered into the echo sounder's RAM (Random Access Memory) and archived for the purpose of its further extraction and analysis.

7.2. Echo sounders basic parameters

According to the International Rules for the Fitting of Ships with Echo Sounders and the Performance Standards for Echo Sounders, regulation 19 requires that echo sounders be fitted on all passenger ships and cargo ships of 300 gross tonnage. t. and more.

Operational requirements for echo sounders.

In accordance with resolution MSC.74 (69), the echo sounder must be able to measure depths below the transmitter from 2 to 200 m at ship speeds up to 30 knots. An echo sounder must have two measuring ranges: from 0 to 20 m and from 0 to 200 m.

Accuracy of measuring depths during rolling ±10° and pitching of the vessel:

- ±0.5 m on a 20 m scale, or

- ±5.0 m on a 200 m scale, or

- ±2.5% of the measured depth (whichever is greater).

The main method of presenting measured depths is graphical. The depth record must be visible for 15 minutes with time stamps (with an interval of no more than 5 minutes). It should be possible to store a record of the measured depth and the corresponding time for 12 hours.

Maximum range.

The main operational parameter of the echo sounder is its maximum range, which is understood as the maximum depth or horizon distance at which the intensity $\boldsymbol{I_{min}}$ and pressure $\boldsymbol{p_{min}}$ of the acoustic wave at the receiving point are the smallest at which it is possible to isolate the signal against the background of acoustic interference. A distinction is made between the energy range of action for vertical sounding of the water column and the geometric range for horizontal sounding.

The sound field of the reflected wave is determined by three main factors: the reflection coefficient (the ratio of the acoustic resistance of water and soil), the structure of the soil and the bottom topography.

Parameters of the probing pulse.

In piezoelectric transducers, for their excitation, electrical impulses are used in the form of 30–40 oscillations of the operating frequency, the envelope of which has a rectangular shape of a certain duration and with a certain repetition rate.

The pulse duration $\boldsymbol{\tau}$ for modern echo sounders ranges from 0.5 to 100 ms.

Pulse repetition rate.

The frequency of sendings ***fp*** depends on the projected maximum depth $\boldsymbol{h_{max}}$, the range of values of the calculated sound speed and determines the speed of obtaining information about reflecting objects, i.e. the number of echo signals per unit of time. In other words, each signal sent must be uniquely identified as a reflected one and not overlap with others.

Operating frequency.

This is one of the main technical characteristics of the echo sounder.

For reliable measurement of minimum and maximum depths, two operating frequencies are used: high - for measuring shallow depths and low - for measuring large depths. The specifications of modern navigational echo sounders often list two frequencies, such as 200 kHz and 50 kHz.

The width of the antenna's directivity.

This parameter of the navigation echo sounder is calculated in such a way that, under conditions of pitching of a given intensity, reliable echo signal reception is ensured.

Accuracy of measuring depths during rolling ±10° and pitching of the ship:

- ±0.5 m on a 20 m scale, or

- ±5.0 m on a 200 m scale, or

- ±2.5% of the measured depth (whichever is greater).

The main method of presenting measured depths is graphical. The depth record must be visible for 15 minutes with time stamps (with an interval of no more than 5 minutes). It should be possible to keep a record of the measured depth and the corresponding time for 12 hours. It is measured in degrees at the level of 0.7 of the maximum pressure value and is usually 25 - 35o for measurements of small depths and 7 - 15o for measurements of great depths.

Resolution in depth (range).

The minimum distance between objects located one after the other on the line of the sound beam, which the echo sounder is still able to distinguish and fix it on the recording device, is called the depth resolution. It will depend on the duration of the probing pulse τ and in real conditions will be approximately (0.7 - 1.2) s τ.

Resolution in direction.

It is determined by the minimum angle between objects located at the same distance from the echo sounder antenna, at which these objects can be recorded separately on the recording device. Depends on the width of the directivity characteristic of the antenna and the resolution of the indicator screen.

Echo sounder accuracy.

The accuracy of measuring the projected depth by a navigation echo sounder is determined by errors: instrumental, due to the deviation of the actual speed of sound from the calculated one, due to the bottom slope, caused by rolling, hydroacoustic interference, etc.

When calculating the echo sounder, the speed of sound propagation in water is assumed to be constant co = 1500 m/s. However, in real conditions, the speed of sound is not the same in different areas of the World Ocean and can be in the range of 1440 - 1580 m/s. Hence, the correction Δh to the measured depth h_{mes} is determined by the formula:

$$\Delta h = h_{mes}(c/c_o - 1).$$

The maximum deviation of the sound speed from the calculated one practically does not exceed 5%, therefore, the measurement error in the limiting case will also not exceed 5% and may not be taken into account in navigation echo sounders.

When the seabed is tilted, the echo sounder will register not the depth strictly under the keel, but the smaller one, which is determined from the geometric ratios of the angle of inclination of the seabed ε and the angle of the width of the radiation pattern.

Practice shows that this error begins to affect the accuracy of measurements at $\varepsilon > 15°$. Even at large angles of inclination of the seabed, the echo sounder measures the minimum distance to the ground, so this correction can be ignored in navigation echo sounders.

Modern navigation echo sounders are multifunctional, have several measurement ranges up to a depth of 1000 m, and the measurement accuracy is ± 2% of the measured depth.

8. SHIP SPEED MEASUREMENT

Information about the ship's speed is used to solve the problem of developing the current position coordinates in all navigation complexes and systems.

Requirements for the accuracy of the vessel's speed measuring by autonomous means - logs are determined by the tasks being solved. Logs are divided into:

a) absolute - measuring the ship's speed relative to the ground;

b) relative - measuring the ship's speed relative to the aquatic environment or the underlying surface.

According to the physical principle underlying the measurement of speed, the logs are divided into: hydrodynamic; induction; hydro-acoustic Doppler, radio Doppler; hydro-acoustic correlation, etc.

According to the number of measured parameters, logs are divided into:

a) single-component - measuring the speed in the fore-and-aft direction of the ship (***Vx***);

b) two-component - measuring the speed in the fore-and-aft direction and in the direction perpendicular to it (***Vx, Vy***).

Today, when solving general problems of navigation, as autonomous devices, the following are used: induction, hydro-acoustic Doppler and hydro-acoustic correlation logs [2 - 4, 13, 14].

8.1. Electromagnetic (induction) logs

The principle of operation of the relative induction log is based on the law of electromagnetic induction, formulated by M. Faraday in 1831. According to this law, the e.m.f. induction ***E*** in an electrically conductive circuit is proportional to the rate of change of the magnetic flux ***Φ*** through the surface ***S***, limited by this circuit:

$$E = -\frac{d\Phi}{dt}.$$

The minus sign shows that the induction current is directed in such a way that its magnetic field prevents a change in the magnetic field that caused the appearance of the induction current (E. Lenz's rule).

The magnetic flux or the flux of the magnetic induction vector ***B*** through any small area ***dS*** is expressed by the product of the projection of the vector ***B*** onto the normal to this area, i.e. at ***B*** perpendicular to ***dS***, the change in the magnetic flux is:

$$d\Phi = d\,(BS).$$

Magnetic induction ***B*** characterizes the magnitude and direction of the magnetic field and is numerically equal to ***the force with which the magnetic field acts per unit length of the conductor located perpendicular to the direction of the field and if a current of one unit flows through the conductor.***

The current itself in the conductor (if the current is not previously passed) can occur in two cases:

- in a constant magnetic field, when the conductor crosses the lines of magnetic induction;

- in an alternating magnetic field - due to the vortex electric field, which is generated in space when the magnetic field changes in time.

The phenomenon of electromagnetic induction also occurs in sea water when it moves relative to a magnetic field. Using this phenomenon, it is possible to build an inductive sensor for an electrical signal proportional to the ship's speed.

In modern induction (electromagnetic) logs, a sensor is used (induction transducer ***ИП***), the diagram of which is shown in Fig. 8.1. In a sealed cylindrical housing ***1*** there is an electromagnet ***2***, the winding of which is fed with alternating current with a frequency of 50 Hz (***~U***). In the lower end part of the sensor, electrodes ***m*** and ***n*** are installed, which protrude together with the transducer through the bottom of the vessel and come into contact with water. The sensor is fixed so that the line connecting the electrodes is perpendicular to the ship's fore-and-aft-line.

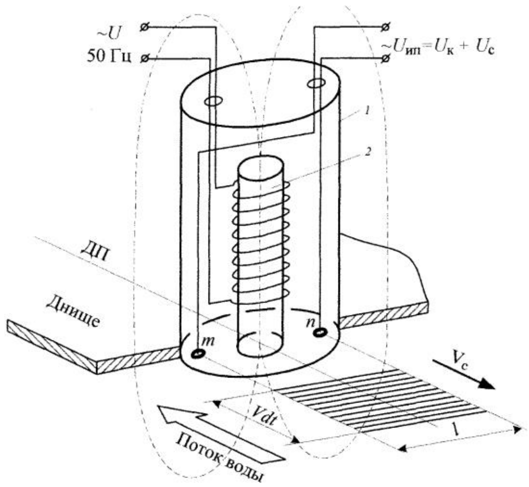


Fig 8.1 Induction transducer

An electromagnet creates an alternating magnetic field that moves with the vessel relative to the water. Sea water can be represented as a set of parallel conductors forming a plane moving between the electrodes. That is, when the vessel moves at a speed ***Vc***, points ***m*** and ***n*** will touch more and more new conductors formed by sea water.

Thus, the effect of the movement of the conductor in an alternating magnetic field is created - an e.m.f. appears, induced in sea water between the electrodes. By measuring this e.m.f., which depends on the speed of the water flow under the bottom of the vessel, we obtain the value of ***Vc*** relative to the water.

The signal of the induction transducer consists of two parts and is supplied to the measuring circuit of the device in the form of voltage.

$$\sim U_{ИП} = U_к + U_c,$$

where $\sim U_к$ – interference, which is called quadrature;

$\sim U_c$ – useful signal, depending on the speed of the vessel.

In the measuring part of the log, the quadrature interference is separated from the useful signal and eliminated.

The variable useful signal ***Uc*** is then converted into a direct current signal, and it, in turn, is converted into pulses, the duration τ_s of which is proportional to the ship's speed. Further, these pulses are filled with pulses of the reference frequency generator and their number, of course, depends on the duration τ_s, i.e. - on the speed of the vessel. Information about the speed in the form of a digit-pulse code is decoded and in digital form comes to the indicators.

Information about the distance traveled is presented as the sum of the counting pulses received at the input of the distance counter. The frequency of these pulses is determined by the current speed of the vessel. Thus, the distance traveled will be proportional to the total number of these pulses.

The induction log, can measure not only the longitudinal relative, but also the transverse component of the ship's speed, i.e. determine the ship's drift.

To do this, the log's induction transducer is supplied with an additional pair of measuring electrodes, and the vector of the vessel's full speed and its drift are calculated from the obtained two velocity components.

The induction log has errors, which are compensated by the log's total correction ΔV. This correction is a certain function of the ship's speed $\Delta V = f\,(Vc)$ and can be represented as the sum of three components

$$\Delta V = a + bV_C + c(V_C),$$

where a – constant, bV_c – linear, $c(V_c)$ – non-linear components of correction.

Induction logs used on transport ships make it possible to measure the relative speed of the vessel with an error of up to 0.2 knots.

8.2. Hydroacoustic Doppler logs

The principle of operation of the hydro-acoustic absolute Doppler log is based on the Doppler effect, which is as follows: if the sound source or receiver move relative to each other, then the frequency of the received signal differs from the frequency of the emitted signal.

If the source moves at a speed v (Fig. 7.2) towards the receiver, that is, it catches up with the wave emitted by it with a frequency f_o, then the wavelength:

$\lambda_1 = (c - v) / f_o$ i.e. decreases;

where c is the speed of wave propagation in the medium.

If the source is moving away from receiver, then the wavelength $\lambda_2 = (c + v) / f_o$ increases.

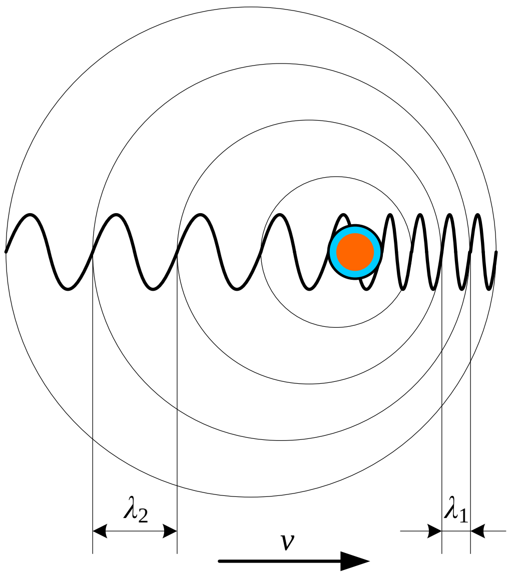


Рис. 6.2. К пояснению эффекта Доплера

In a Doppler hydro-acoustic log, both the oscillations' transmitter and receiver are located on the ship. Moreover, the transmitter forms a narrowly directed, 3-6° solid angle ultrasonic beam (Fig. 7.2), at an optimally chosen angle $\boldsymbol{\alpha_1}$ = ***60°***.

The wavelength of the initial radiation:

$$\lambda_o = c / f_o,$$

where ***c*** is the speed of sound in sea water.

Since the radiation source is moving, the speed of removal of the transmitted wave from the ship is determined by the speed of sound ***c*** and the projection of the velocity vector $\boldsymbol{V_x}$ onto the transmission direction: $\boldsymbol{c_1 = c - V_x \cos\alpha_1}$.

Then the wavelength received in the conditional receiver - a fixed point $\boldsymbol{O_1}$ on the seabed,

$$\lambda_1 = (c - V_X \cos\alpha_1)/f_0.$$

Turning to frequency, we can write

$$f_1 = f_0\left(\frac{c}{c - V_X \cos\alpha_1}\right), \qquad (8.1)$$

which explains the Doppler effect: in this case, the frequency of the received signal is greater than the frequency of the sent one.

The beam scattered from the seabed (due to the unevenness of the sea surface) reaches the receiver at an angle $\boldsymbol{\alpha_2}$, since the vessel has shifted during the propagation of the beam.

The speed of the reflected signal approaching the moving receiver is determined by the speed of sound ***c*** and the projection of the velocity vector $\boldsymbol{V_x}$ onto the direction of the reflected beam: $\boldsymbol{c_2 = c + V_x \cos\alpha_2}$.

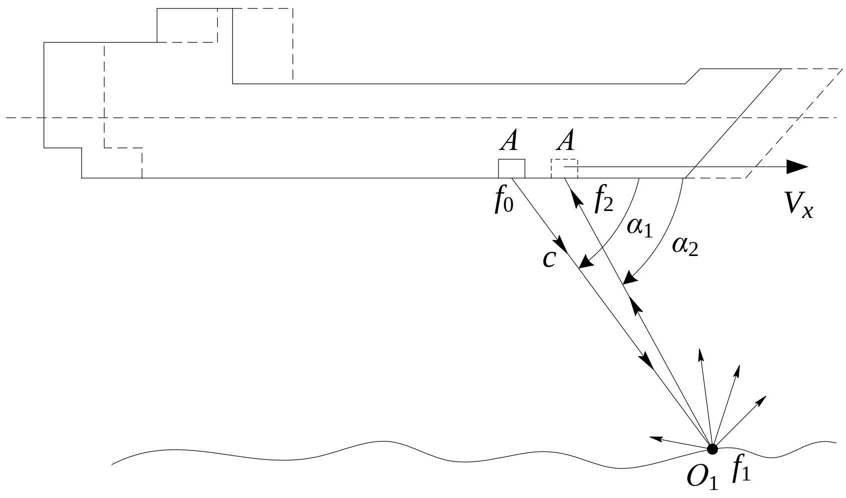


Fig. 8.3. The hydro-acoustic Doppler log principle of operation

If we assume that the speed of the vessel is small and ***α₁* ≈ *α₂* = *α***, then as a result, the frequency of the received oscillations, taking into account (7.1), can be represented as:

$$f_2 = \frac{c_2}{\lambda_1} = f_o\left(\frac{c + V_x \cos\alpha}{c - V_x \cos\alpha}\right),$$

Having performed the appropriate mathematical transformations of this expression […], we can come to the conclusion:

$$f_2 = f_o\left(1 + \frac{2V_x \cos\alpha}{c}\right).$$

Then the difference between the frequencies of the echo signal that came to the antenna from the ground and the transmitted signal (Doppler frequency shift):

$$f_Д = f_2 - f_o = \frac{2 f_o V_x \cos\alpha}{c}. \qquad (8.2)$$

From equality (7.2) we have:

$$V_x = \frac{f_Д}{2 f_o} c \sec\alpha.$$ – ship's speed longitudinal component.

In real conditions, a change in the angle α during roll, trim, pitching, the influence of the vertical component of the ship's speed on the measured signal leads to significant errors. For this reason, the single-beam log scheme has not applied.

In practice, two-beam Doppler systems are used, in which an ultrasonic wave is transmitted along the diametrical plane of the vessel towards the bow and stern at the same angle α (Fig. 8.3).

The frequency of the transmitters in both channels is the same and strictly fixed. Acoustic system receivers receive signals of the following frequencies:

$$f_{\text{н}} = f_{\text{о}}\left(1+\frac{2V_x\cos\alpha}{c}\right); \qquad f_{\text{к}} = f_{\text{о}}\left(1-\frac{2V_x\cos\alpha}{c}\right),$$

where $f_{\text{н}}$ и $f_{\text{к}}$ – frequencies of received signals from the bow and stern of the vessel, respectively.

Doppler frequency shift between the echo signals from the bow and stern transmission in this case:

$$f_{\text{Д}} = f_{\text{н}} - f_{\text{к}} = \frac{4f_{\text{о}}V_x\cos\alpha}{c}, \quad \text{тогда } V_x = \frac{f_{\text{Д}}}{4f_{\text{о}}}c\sec\alpha.$$

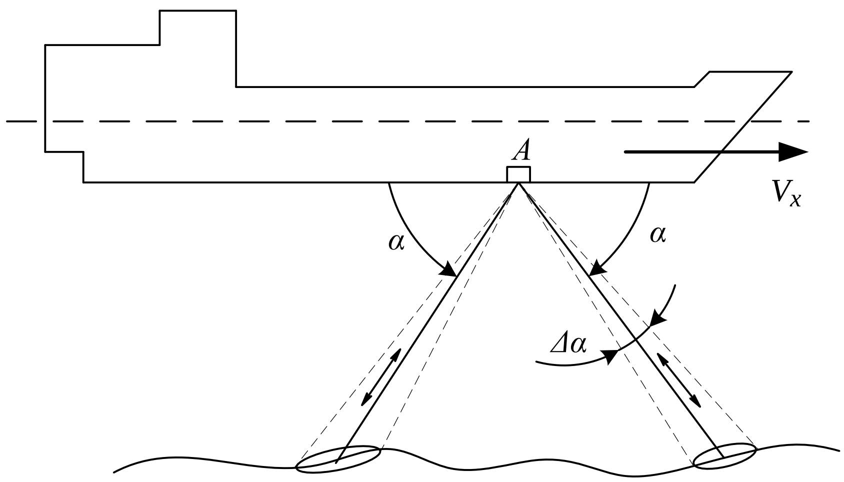


Fig. 8.4. Dual beam Doppler system

A dual-beam Doppler system allows to significantly reduce the errors inherent in a single-beam Doppler log, however, only the longitudinal component of the ship's speed is determined. To determine not only the longitudinal, but also the transverse component of the vessel's speed, three- and four-beam antennas are used. And if it is necessary to have information about the movement of the ship's extremities, then six- (mostly) and eight-beam Doppler systems are used, as shown in Fig. 8.4.

Using a pair of beams 1 and 3, the longitudinal component of the ship's speed $\boldsymbol{V_x}$ is determined, and using a pair of beams 2 and 4, the transverse component of the speed $\boldsymbol{V_y}$. In the computing device of the log, the ground speed of the vessel $\boldsymbol{V_c}$ and the drift angle $\boldsymbol{\beta}$ are calculated. A pair of beams 5 and 6 of the aft antenna unit ***Ak*** provides information about the transverse component of the speed of the aft part of the vessel.

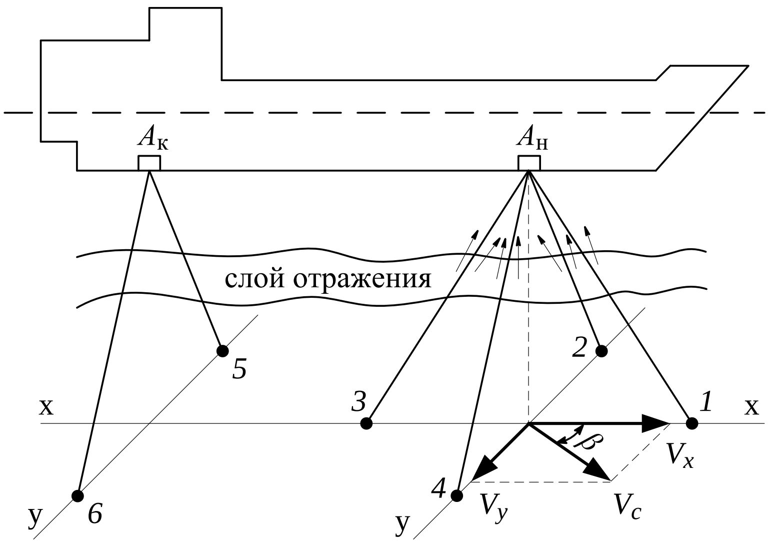


Fig. 8.5. Six-beam Doppler system

The described system is installed on large-capacity vessels and is intended not only for navigational purposes, but also for measuring small transverse velocity components of the bow and stern ends of the vessel, which is important when performing mooring operations.

Most designs of Doppler logs have corrective devices that compensate for errors caused by a change in the speed of sound in sea water in two ways: the water temperature in the antenna area and its salinity.

The working depths of absolute Doppler logs are in the range of 200 - 300 m. When sailing at greater depths, the logs are switched manually or automatically to work in relative mode. In this case, the log will operate on the basis of signals reflected from water layers lying at depths of 20–60 m [13] – fig. 7.4. These layers are more characterized by the presence of various inclusions in sea water - microparticles, bioorganisms, air bubbles.

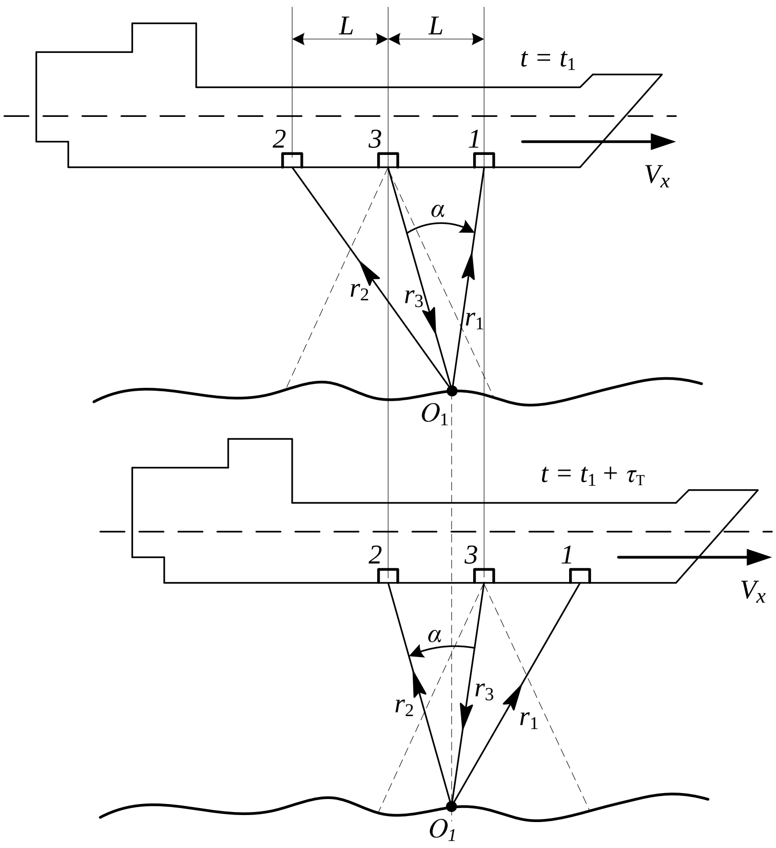
The accuracy of readings of Doppler logs in absolute mode is quite high and at angles of pitch, trim, roll, not exceeding 2 - 3°, the total error ranges from 0.1 to 3%.

8.3. Hydro-acoustic correlation log

The principle of operation of the hydro-acoustic correlation log is based on measuring the time shift between identical acoustic signals received by two ship antennas separated by a certain distance. The signals are reflected from the ground after its radiation by ship’s transmitted antenna.

Let us explain the indicated principle of operation for the case of measuring one - the longitudinal component of the ship's speed.

In the bottom of the vessel along its fore-and-aft line (Fig. 8.5), one transmitting 3 and two receiving 1 and 2 hydro-acoustic antennas are installed. The receiving antennas are separated from the transmitting antenna by exactly the same base distance L. The characteristics of the radiation patterns of all three antennas are identical (within 30°), they mutually overlap and their axes are oriented vertically downwards. The distance between the acoustic antennas is 3 - 5 cm, and the operating frequency of the radiation is 150 kHz.



8.6. Correlation log principle of operation

The transmitting antenna 3 has a fairly wide radiation pattern (shown by a dotted line) and irradiates at the bottom a set of many elementary reflectors randomly located, including the elementary reflector $\boldsymbol{O_1}$.

The echo signal from reflector $\boldsymbol{O}_1$ is received by antennas 1 and 2 at time $\boldsymbol{t = t_1}$. The amplitude and phase of the signal received by antenna 1 is determined by the geometry of the beams r_3 and r_1 (angle $\boldsymbol{\alpha}$).

When the ship travels the distance $\boldsymbol{L}$, the position of the antennas relative to the ground will change: the geometry of the beams $\boldsymbol{r'_3}$ and $\boldsymbol{r'_2}$ is similar to the geometry of the beams $\boldsymbol{r_3}$ and $\boldsymbol{r_1}$ (the same angle $\boldsymbol{\alpha}$), except for the direction of propagation of the acoustic wave. However, a change in the direction of signal propagation does not lead to a change in its amplitude and phase.

This means that the signal received by the aft antenna 2 from the elementary reflector $\boldsymbol{O_1}$ at the time $\boldsymbol{t = t_1 + \tau_T}$ will be the same as at the previous time $\boldsymbol{t_1}$ received by the bow antenna 1, but with some delay $\boldsymbol{\tau_T}$.

In other words, the stern antenna signal repeats the shape of the bow antenna signal, but lags behind it in time by a certain interval $\boldsymbol{\tau_T}$, called the transport shift or transport delay.

This delay is equal to the time required for a vessel with a speed $\boldsymbol{V_x}$ to cover half the distance between the receiving antennas: $\boldsymbol{\tau_T = L/V_x}$.

Then the problem of determining the speed of the vessel $\boldsymbol{Vx}$ is reduced to determining the time shift $\boldsymbol{\tau_T}$ between the signals received by the diversity antennas at a known distance $\boldsymbol{L}$, i.e. $\boldsymbol{Vx = L/\tau_T}$.

Unfolded in time due to the movement of the vessel, the overall picture looks like a continuous formation of two identical functions $U_1(t)$ and $U_2(t)$ shifted in time, which are of a stationary random nature.

For this reason, the problem is solved on the basis of an analysis of the degree of correlation between the two indicated functions.

The degree of such a relationship is characterized by the cross-correlation function $R_{1,2}(\tau)$, which takes on a maximum value if there is no time shift between the functions $U_1(t)$ and $U_2(t)$ or, relatively speaking, when the functions $U_1(t)$ and $U_2(t)$ are combined. The condition for this is the equality $\boldsymbol{U_2(t) = U_1(t - \tau_T)}$.

To fulfill this condition, at the next computing cycle, a time delay $\boldsymbol{\tau_z}$ is introduced into the measuring path of the bow antenna, changing its value by $\Delta\tau$, the cross-correlation coefficient $\rho_{1,2}(\tau)$ of the functions $U_1(t)$ and $U_2(t)$ is calculated and its current value is compared with previous. Based on the found maximum value $\rho_{1,2}(\tau)$, it is determined that either $\boldsymbol{\tau_з = \tau_T = L/V_x}$.

Thus, by adjusting the value of the time delay $\boldsymbol{\tau_z}$ and continuously maintaining the maximum value of the cross-correlation coefficient $\boldsymbol{\rho_{1,2}(\tau)}$, it is possible to determine the instantaneous value of the longitudinal component of the ship's speed $\boldsymbol{V_x}$.

To determine the full velocity vector of the vessel and the drift angle, at least three receiving antennas are used - their arrangement may be different, but two of them are located in the transverse plane of the vessel.

The hydro-acoustic correlation log is an absolute log, but it is also used as a relative one (according to the principle considered in the hydro-acoustic Doppler log). Since the axis of the radiation pattern of the radiating antenna is directed vertically downwards, the depth of the sea under the keel of the vessel is measured simultaneously with the measurement of the absolute speed.

The speed measurement error is ± 0.1 knots, the distance traveled is up to ± 0.2%, the depth under the keel is ± 1%.

9. AUTOPILOTS

9.1. Principle of operation

One of the areas of a ship motion control automation is limited to solving a relatively simple problem - stabilizing the ship on a given heading. The corresponding control systems are called autopilots and are widely used in the fleet.

Heading stabilization consists in maintaining a constant heading value by compensating by the rudder for heading deviations caused by random external influences ***f*** (Fig. 9.1). Here, the principle of control is used according to the deviation by the angle $\boldsymbol{\psi}$ of the current heading ***K*** from the one set for the stabilization of the heading Kz. The result is the formation of the rudder shift value $\boldsymbol{\beta}$ to keep the ship's heading, depending on the deviation of the current heading from the given one [2, 3, 16].

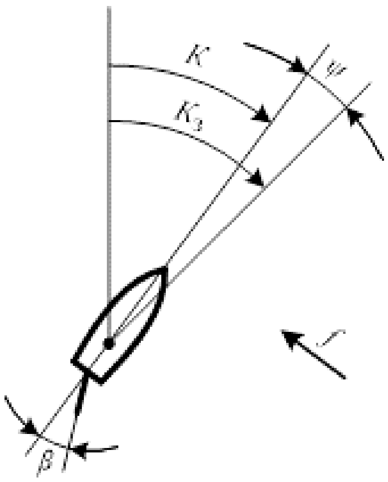


Fig. 9.1 Ships deviation from given heading

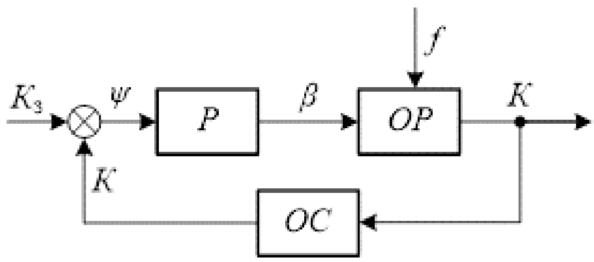


Fig.9.2. General diagram of the automatic control system

Like any automatic control system (ACS), the ship's heading ACS includes three main elements (Fig.9.2): the control object OP (ship), external feedback OC and regulator P. The ship as a control object experiences disturbing and control actions. Disturbing influences ***f*** (wind, waves, current) are random in nature and lead to the deviation of the vessel from the given heading. The heading ***K*** of the ship is controlled by heading indicator or other means that gives similar information, which forms an external feedback in the control system. At the input of the system, the set value of ***Kz*** and the actual ***K*** of the headings are compared, and their difference ψ is fed to the input of the regulator.

The purpose of the regulator is to transform, according to a certain law, the deviation ψ of the ship from the given heading into the deviation β of the rudder. With manual control, the function of the regulator is performed by the helmsman. Rudder deflection will cause a control action on the vessel, which is aimed at compensating for the disturbing effect.

Thus, heading ACS is a tracking system that works on the vessel's deviation from the given heading caused by the action of external disturbances or setting influences.

The quality of regulation is determined by the law $\beta = f(\psi)$, according to which the rudder is shifted depending on the current value and the nature of the change in the ship's deviation ψ from the given heading. In autopilot regulators, a proportional-differential-integral law is implemented, according to which a signal is generated that determines the required rudder shift. Such a regulator is called a PID regulator.

9.2. Proportional control law

The equation of the simplified linear model of the ship's yaw under the action of a constant perturbation ***fo = const*** has the form:

$$T_C\ddot{\psi} + \dot{\psi} = k_C\beta + f_O, \qquad (9.1)$$

where T_c – vessel time constant;

k_c – vessel's transfer coefficient by the control action.

The values of the parameters of the ship model (8.1) for modern ships at speeds of 10÷17 knots lie within the limits: T_c = 10÷70 s.; kc = 0.03÷0.15 s-1 [16].

With a proportional control law, the rudder shift is carried out according to the law:

$$\beta = -k_1\psi, \qquad (9.2)$$

где k_1 – yaw angle transfer coefficient, which determines the ratio of the rudder angle to the angle of the ship's deviation from a given heading.

The minus sign on the right side means that the control signal is always directed in the direction of decreasing the value of $\boldsymbol{\psi}$. Then equation (8.1), taking into account (8.2), takes the form:

$$T_C\ddot{\psi} + \dot{\psi} + k_C k_1 \psi = f_O. \tag{9.3}$$

It follows that in the steady state operation ($\ddot{\psi}$ = 0; $\dot{\psi}$ = 0; $\psi = \psi_{ст}$) the heading stabilization system will have a static error

$$\psi_{ст} = \frac{1}{k_C k_1} f_O$$

that is, after the completion of the transition process with a proportional control law (a P-regulator is used), the ship does not go to a given heading.

With a proportional control law:

- there is a static error $\boldsymbol{\psi_{cm}}$, over time (with constant external disturbances) one-sided drift of the vessel from the line of a given path will accumulate;

- the transient process is unstable, the overshoot $\boldsymbol{P}$ is significant, the ship may "swing" - this is due to the difficulty of selecting the control parameter $\boldsymbol{k_1}$;

- the time of the transient process $\boldsymbol{t_r}$ increases, which is explained by the large inertia of the vessel.

Thus, the P-regulator cannot be considered satisfactory for the automatic stabilization of the course of ships.

9.3. Proportional-differential control law

To improve the dynamic characteristics of the control system, the derivative of the controlled value is introduced into the control law, i.e. use a proportional-differential (PD) control law, in which the rudder is shifted according to the angle and angular rate of yaw:

$$\beta = -(k_1\psi + k_2\dot{\psi}), \tag{9.4}$$

where k_2 is the yaw rate transfer coefficient, which determines the ratio of the rudder angle to the yaw rate.

Substituting equation (8.4) into the original ship motion equation (8.1), we obtain

$$T_C\ddot{\psi} + \dot{\psi} + k_C k_1 \psi + k_C k_2 \dot{\psi} = f_O, \tag{9.5}$$

from which it follows that in the steady state of operation ($\ddot{\psi} = 0$; $\dot{\psi} = 0$; $\psi = \psi_{\text{CT}}$) the heading stabilization system will have the same static error as with the proportional control law

$$\psi_{\text{CT}} = \frac{1}{k_C k_1} f_O,$$

However, the solution and analysis of equation (8.5) show that the nature of the transient process will be different and the quality of regulation in this case will improve significantly.

Let us assume that the angle $\boldsymbol{\psi}$ changes with time as shown in Fig. 8.3. It also shows the change in angular velocity.

In the time interval 0–t_1, the angle $\boldsymbol{\psi}$ and the angular velocity have the same signs. This means that the control signal will be increased, the rudder will be laid down by a larger amount, and the ship will deviate from the course line by a much smaller angle.

At the moment $\boldsymbol{t_1}$, when the vessel begins to return to the given heading, the sign of the derivative changes to the opposite, and the sign of the angle $\boldsymbol{\psi}$ remains the same. The total control signal in the interval $\boldsymbol{t_1}$–$\boldsymbol{t_2}$ will be reduced, i.e. entering a derivative will slow down the return of the vessel to the heading. This is exactly what is needed to slow down the ship's inertia.

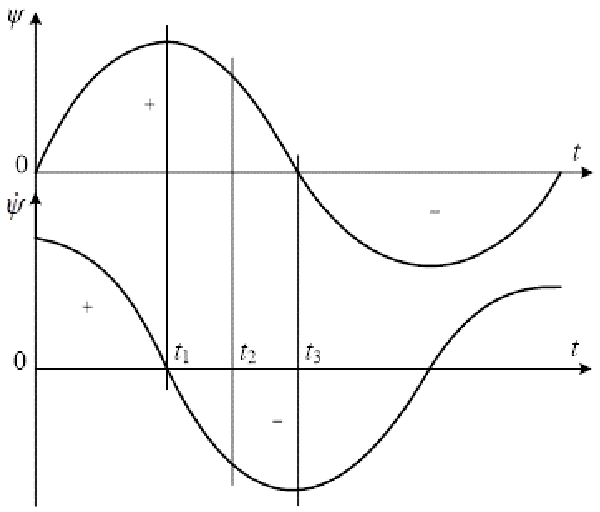


Fig. 9.3. Use of the derivative with respect to the yaw angle

At some time t_2, the rudder will be set in the ship's DP, since the levels of the signals at the angles $\boldsymbol{\psi}$ and $\dot{\psi}$ will be equal, but their signs are opposite. Starting from time $\boldsymbol{t_2}$, the rudder will deviate towards the opposite side, although the ship has not yet returned to the set heading. In this way, the vessel is automatically kept on heading.

At the moment t_3 the ship will cross the heading line, but this will happen with the rudder already laid in the opposite direction, due to which the ship's deviation from the heading will be less than when steering only in the yaw angle. In the future, the whole process is repeated.

Comparing the operation of a PD controller with a P controller, we can note:

- with a proportional-differential control law, the function of automatically keeping the vessel on course is performed;

- the transient process of regulation becomes stable, the overshoot and regulation time decrease;

- it is possible, by choosing the control parameter k_2, to ensure the satisfaction of the requirements for the quality of control, depending on the navigation conditions of the ship;

- under external action, the static error with the PD control law remains the same as with the proportional law.

Thus, derivative control improves the quality of regulation. Autopilots with a PD control law have found practical application and are produced by industry.

9.4. PID-control low

One of the effective measures to compensate for the static error that occurs with the P- and PD-laws of control is the introduction of a signal into the control law by the integral of the heading angle. In this case, the rudder shift is carried out according to the proportional-differential-integral (PID) control law

$$\beta = -\left(k_1\psi + k_2\dot{\psi} + k_3\int_0^t \psi dt\right), \tag{9.6}$$

where $\boldsymbol{k_3}$ is the transmission coefficient by the integral of the yaw angle, which determines the ratio of the rudder angle to the average value of yaw over time $\boldsymbol{t}$.

Equation (7.1), taking into account expression (8.6), takes the form

$$T_c\ddot{\psi} + \dot{\psi} + k_c k_1\psi + k_c k_2\dot{\psi} + k_c k_3\int_0^t \psi dt = f_o. \tag{9.7}$$

Differentiate equation (8.7). Taking into account that when ***f₀ = const***, $\frac{df_0}{dt}=0$ we get:

$$T_C\dddot{\psi}+\left(1+k_C k_2\right)\ddot{\psi}+k_C k_1\dot{\psi}+k_C k_3\psi=0. \qquad (9.8)$$

It follows that the static error (under condition $\dddot{\psi}=\ddot{\psi}=\dot{\psi}=0$) is equal to zero ($\psi = \psi_{CT} = 0$). Such a control system is called astatic..

The physical essence of control by the integral of the heading angle is as follows.

A constant external disturbance (for example, a side wind or asymmetry of the propeller stop on multi-propeller ships) leads to the fact that a constant component appears in the composition of the ship's oscillations on the course. It is said that the ship is asymmetrically prowling on the heading. This leads to the systematic demolition of the ship from the track. The integrating device measures the magnitude of this asymmetry and introduces it into the autopilot as an additional signal.

In this case, a certain, constant for the given conditions, shift of the neutral position relative to the center plane of the vessel appears at the rudder. The magnitude and sign of this shift are such that the hydrodynamic effects on the ship arising from it completely compensate for the external disturbance.

The integral signal accumulates slowly and in the initial period of the transient process does not affect the ship's control. In the future, the transitional process occurs in accordance with the solution of equation (8.8), which is much higher than in the absence of an integral law.

When the autopilot is in “Follow-up” mode (handwheel control), the system does not respond well to slow altering in giving heading set. Therefore, in this mode of operation, the integrating unit of the device for modern autopilots is automatically turned off.

When designing autopilot parameters $\boldsymbol{k_1}$, $\boldsymbol{k_2}$, $\boldsymbol{k_3}$ are chosen such that the stability of the control system is ensured and that the transient process has the specified characteristics. Thus, the coefficient $\boldsymbol{k_1}$ is set depending on the loading of the vessel, $\boldsymbol{k_2}$ is practically selected within 0÷50 sec. (on the remote control of the autopilot there is a regulator “Derivative”), $\boldsymbol{k_3}$ lies within the limits of 0÷0.01 s^{-1}.

9.5. Autopilot functional diagram

Modern autopilots have wide functionality [3, 17], the main of which are: keeping the vessel on the given heading – "Automatic" mode; altering heading by a given value – "Follow-up" mode. Let us consider in more detail in functional terms the operation of the heading automatic control system in the "Automatic" mode. A typical block diagram of the heading ACS is shown in fig. 8.5.

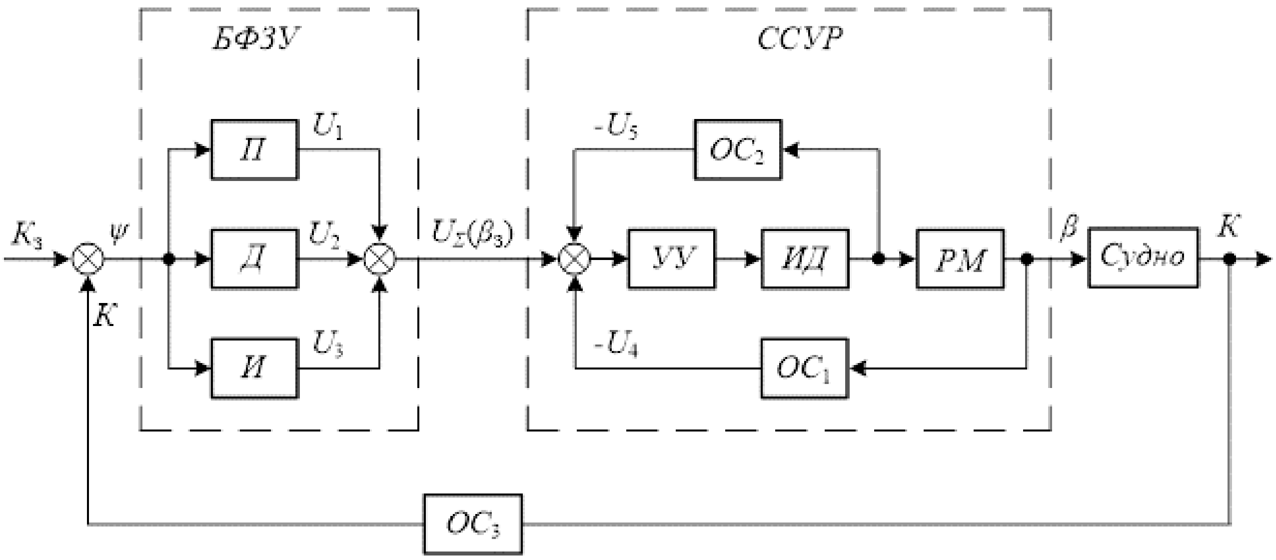


Fig. 9.4. Typical block-diagram of the conventional autopilot

Regardless of the design features, the ACS controller can be divided into two parts: the БФЗУ block for the formation of the control law and the servo steering system ССУР. The controller and the control object (ship), covered by feedback, with the help of which information about the state of the control object is transmitted to the input of the controller, form a closed control system.

In autopilots that implement the PID control law, the БФЗУ is presented in the form of three units: П - proportional; Д - differential; and – И - integral.

The ССУР tracking system includes: УУ - amplifying device; ИД - executive motor; РМ - steering machine; OC_1 - internal hard negative feedback from the steering sensor; OC_2 - internal flexible negative feedback from the executive мотор.

In the automatic mode of control, the autopilot circuit is connected to the gyrocompass, the current readings of which, as external negative feedback OC_3, are fed to the input of the control system. Deviation ψ of the vessel's heading K from the given one $K_з$ is fed to the input of the БФЗУ, which generates three signals: U_1, U_2 and U_3.

The signal $\boldsymbol{U_1 = k_1\psi}$ is generated by the БФЗУproportional unit and is the main control signal proportional to the ship's yaw angle.

The signal $\boldsymbol{U_2 = k_2}\dot{\psi}$ is created by differentiating the signal $\boldsymbol{U_1}$. The $\boldsymbol{U_2}$ signal improves the conditions for stabilizing the ship on a given heading, providing the damping of the ship's oscillations relative to the given heading. The level of influence of the $\boldsymbol{U_2}$ signal can be set depending on the state of the sea.

The signal $U_3 = k_3\int_0^t \psi dt$ is created by integrating the $\boldsymbol{U_1}$ signal. The presence of the $\boldsymbol{U_3}$ signal makes it possible to exclude the asymmetric yaw of the vessel due to various external influences. This signal provides an additional rudder shift at a certain constant angle, which compensates for the influence of an external asymmetric disturbance.

The listed signals are summed up and fed to the input of the amplifying device in the form of a total control voltage $\boldsymbol{U_\Sigma = U_1 + U_2 + U_3}$, the change of which in time determines the specified rudder laying law - the angle $\boldsymbol{\beta_3}$. The amplified signal is fed to the executive motor of the ID, which drives the steering machine PM of the ship, and, consequently, the rudder.

Simultaneously with the beginning of the rudder shift, the input of the servo system via the feedback channel $\boldsymbol{OC_1}$ receives the signal $\boldsymbol{U_4 = k_4\beta}$, which is proportional to the value of the rudder angle. This signal is generated in the steering sensor mechanically connected to the rudder. The signal $\boldsymbol{U_4}$ is always in antiphase with the signal $\boldsymbol{U_1}$. It creates a hard negative feedback.

The rudder shift occurs until the feedback signal $\boldsymbol{U_4}$ is equal to the control signal $\boldsymbol{U_\Sigma(\beta_3)}$. Deviation of the rudder leads to the return of the vessel to a given course. In this case, the control signal $\boldsymbol{U_\Sigma(\beta_3})$ decreases with respect to the signal $\boldsymbol{U_4}$. As a result, the signal at the input of the tracking system alters it’s sign, which leads to return the rudder to its original position. Accordingly, the feedback signal $\boldsymbol{U_4}$ decreases. The rudder shift will stop when both signals are become equal again.

Signal $\boldsymbol{U_4}$ has a limiting effect on the rudder angle. With the increase in sea roughness, the signal level $\boldsymbol{U_4}$ is increased (with the help of a regulator). At the same time, the accuracy of the autopilot deteriorates (the yaw of the vessel increases), but the number of rudder shifts decreases and the load on the steering machine decreases.

The level of signal which fed to the steering machine determines the rudder turn speed. To ensure the stability of the system of the actuator - the rudder and the damping of self-oscillations of the rudder blade, a flexible negative feedback signal OS_2 is introduced, which is proportional to the rudder shift speed: $\boldsymbol{U_5 = k_5}$. The signal $\boldsymbol{U}_5$ is fed to the input of the servo system, where it is added to other signals, and, like the signal

U_4, it is in antiphase with respect to the signal ***U_1***. Its action is manifested in the limitation of the main signal ***U_1*** at large rudder angles.

The average value of yaw in the automatic mode (with the optimal positions of the "Derivative" regulator - signal ***U_2*** and "Feedback coefficient" (KOC) - signal ***U_4***) is approximately 1° for sea waves up to 3 points and does not exceed 3° for sea waves up to 5 points. When the sea is over 5 points, the autopilot ensures that the vessel is reliably kept on course, but the yaw will be more than 3°.

9.6. Adaptive autopilots

The improvement of vessel traffic control systems has led to the creation of autonomous adaptive autopilots [16]. Adaptive autopilots provide optimal, in a certain sense, setting of the system parameters without the participation of a human operator when the state of the control object and the external conditions of navigation (speed, vessel draft, weather conditions, depth under the keel) change. Depending on the implemented principles of adaptation (parametric adaptation with adjustment of the PID controller coefficients), adaptation is carried out with a parametric identification of the object in real time, adaptation with a reference model, direct compensation of disturbing influences, etc.). There are several types of adaptive autopilots.

Adaptive autopilots of the first type are characterized by partial automatic adjustment of system parameters and, as a rule, do not provide full optimization of the system of automated control of the vessel's movement along the course in various navigation conditions.

The second type includes autopilots that perform automatic adaptation of the system using a reference mathematical model (MM) of an object or the entire control system as a whole. In these autopilots, the formation of signals that affect the control parameters is carried out on the basis of an analysis of the quality of keeping the vessel on course using the observed and simulated state variables. An essential feature of these systems is the presence of a mathematical model of the vessel.

The third type of adaptive autopilots includes self-adjusting systems that determine the optimal values of the tuning parameters directly according to a given, mathematically justified, quality criterion. Such a criterion is usually a functional that provides a minimum loss of useful power of the ship's power plant during control and, as a result, a minimum fuel consumption per unit of distance traveled. *The structure of the autopilot includes a microprocessor complex with a set of computational programs*, which receives information from the ship's gyrocompass, log, gyroscopic meter of the angular rate of the vessel's turn, pendulum inclinometer, which measures the rolling period, and also transmits the values of the specified and true rudder turn angles. The sets of control parameters calculated by special programs are stored in the memory block of the ship's microcomputer in the form of a matrix and are selected depending on the ship's speed, the system's frequency bandwidth and the results of minimizing the quality criterion in a closed system.

However, adjusting the coefficients of the autopilot or a partial change in its structure using corrective elements by the indicated methods is carried out only in certain modes of its operation and is not fully adequate to the actual changes in the characteristics of the vessel and external influences.

Recently, a promising class of ***self-organizing adaptive systems*** has appeared. Self-organizing systems are designed to control processes in complex objects (non-stationary nonlinear with random external influences), whose mathematical models are unknown.

The fundamental difference between these control systems and known adaptive systems is that they are built on a combination of structural (functional) adaptation algorithms with parametric adaptation and optimality algorithms.

Optimal control of any object is possible only with optimal information processing - this is the optimal assessment of the state and identification of the parameters and characteristics of the control object according to experimental data. State estimation is the determination of the current values of such process variables that cannot be measured directly or can only be measured with a large error. Identification algorithms allow you to determine the structure of the ship model and restore the parameters of this model.

Autopilot self-organization is carried out using interconnected accepted algorithms for assessing the state of the system, filtering input information, structural and parametric adaptation of an automatically generated ship model, and, finally, automatically determined optimal control actions. Such autopilots fully meet modern requirements.

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