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The ultimate solution to the deviation problem of magnetic compasses

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Abstract

This article has looked into the role of the magnetic compass in providing navigational safety for ships. The existing requirements of the magnetic compass for safe navigation in case the gyro compass breaks-down and in case of terrorists abusing GPS signals do not solve the problems that occur in everyday life. Therefore, a new rational requirement has been proposed for the accuracy and frequency of deviation adjustment work assuring the safety and cost effectiveness of navigation. Vessel owners and masters have responsibilities to ensure that magnetic compasses are maintained in good working order, are adjusted and accompanied by a table or curve of residual deviations. This article has outlined the most urgent problems for the adjustment of magnetic compasses that apply to all ships irrespective of size and navigation area. The proposed method has been verified experimentally.

Introduction

The requirements for the operation of magnetic compasses have been very precisely defined by international rules.

All ships, excluding fishing vessels and pleasure craft under 150 gross tonnages, must be fitted with a magnetic compass or other means to determine and display the vessel's heading independent of any power supply (IMO, 2004).

Each magnetic compass that is required to be carried by the Regulations shall be properly adjusted and its table or curve of residual deviations must be available at all times. Magnetic compasses should be adjusted when (Łusznikow & Pleskacz, 2012):

- they are first installed;
- they become unreliable;
- the ship undergoes structural repairs or alterations that could affect its permanent and induced magnetism;
- electrical or magnetic equipment close to the compass is added, removed, or altered;
- a period of two years has elapsed since the last adjustment and a record of compass deviations has not been maintained, or the recorded deviations are excessive, or when the compass shows physical defects.

Because the magnetism of a new ship can be particularly unstable, the performance of magnetic compasses should be monitored carefully during the early life of a ship, and adjustments made if necessary. Masters are advised that it is essential to check the performance of magnetic compasses particularly after:

- carrying cargoes which have magnetic properties;
- using electromagnetic lifting appliances to load or discharge;
- an accident in which the ship has been subject to severe impact or electrical charges;
- the ship has been laid up or has been lying idle – even a short period of idleness can lead to serious deviations, especially for small vessels.

Every effort should be made to determine the compass deviation and then compass performance should be monitored by frequently recording deviations in the compass deviation book. Compass errors should be determined after every large alteration of course, and at least once every watch when there have been no major course alterations. Checking the compass deviation regularly may reveal the need for repair, testing, or adjustment. In addition, compasses should be inspected occasionally by a competent officer or compass adjuster (Regulations, 1981). In the UK, all adjustments should be made by a compass adjuster who holds a Certificate of Competency as a Compass Adjuster issued by the UK Government. If a qualified compass adjuster is unavailable and the Master considers it necessary, adjustments may be made by a person holding a Certificate of Competency (Deck Officer) Class 1 (Master Mariner). The compass must be re-adjusted by a qualified compass adjuster at the next available opportunity. The date of any adjustment and other details should be noted in the compass deviation book. The position of correctors should be recorded in the compass book and on deviation cards. Because the distances from the coefficients B and C correctors to the standard compass card and to the transmitting element are different, a transmitting magnetic compass will be overcompensated resulting in an error, which can be as much as 2.5° and cannot be corrected. Separate deviation cards should be prepared for the standard compass and the transmitting magnetic compass repeater by comparing headings (Regulations, 1981).

Local regulations also apply. In Russia, for example, the Captain can extend the validity of deviation card by three months, in Australia by three years.

Tendencies to allow for longer time intervals are due to the increased importance of satellite navigation and the reduced role of the magnetic compass. Although sailors understand that the existing requirements for the magnetic compass are obsolete, inconsistencies in this matter are primarily caused by a lack of scientific basis for the solution concept.

Before the advent of GPS (Global Positioning System), or any equivalent satellite system, a continuous monitoring of course indicators was mainly carried out by comparing the true courses obtained from the gyrocompass and from the magnetic compass.

A steel vessel has a certain amount of permanent magnetism in its hard iron and induced magnetism in its soft iron (Denne, 1979; Jurdziński, 2014; Bowdwitch, 2017). Whenever two or more magnetic fields occupy the same space, the total field is the vector sum of the individual fields. Thus, near the magnetic field of a vessel, the total field is the combined total of the Earth's field and the vessel's field. To sum up, in the vessel's immediate vicinity, the two magnetic fields interact.

Modern methods of controlling the indications of gyrocompasses are practically limited to the method of using satellite receivers. On the other hand, in the case of magnetic compasses, practically all other methods have been abandoned, and are now limited to comparing the indications of the magnetic compass and the gyrocompass.

It should be remembered that the comparison between the indications of two devices is a comparison at the level of the accuracy of the device with less accuracy, which is usually a magnetic compass (Ron, 2009; Łusznikow & Pleskacz, 2012; 2016; 2017).

The situation of when the regulations concerning the magnetic compass are outdated but still exist needs to be rectified. This article was aimed at finding a radical and satisfactory solution to this problem, one in which a magnetic compass does not require any deviation adjustment, like the gyro. This formulation of the problem may seem rather bold, but it is very real (Pleskacz, 2017).

This article has outlined the most urgent problems for the adjustment of magnetic compasses that apply to all ships irrespective of size and navigation area. The proposed method has been verified experimentally.

Mathematical description of the deviation of a magnetic compass

The mathematical description of the deviation of the magnetic compass describes the Poisson equations based on the principle of the theorem on uniform magnetization (Łusznikow, 2010; Łusznikow & Dzikowski, 2012):

$$\begin{aligned} X' &= X + aX + bY + cZ + P \\ Y' &= Y + dX + eY + fZ + Q \\ Z' &= Z + gX + hY + kZ + R \end{aligned} \tag{1}$$

where:

X', Y', Z' – projection of the total intensity of the magnetic field on the ship's axes XX, YY, and ZZ;

X, Y, Z – projection of the total force of the ship's magnetic field intensity on the same axes of the Earth's magnetic field;

P, Q, R – projection of the total force of the ship's magnetic field intensity on the ship's axes resulting from the permanent magnetism of hard iron;

a, b, c, d, e, f, g, h, k – Poisson parameters.

From Poisson equations (Vorov, Grigoriev & Ialovenko, 2004) Archibald Smith derived the equation of magnetic compass deviation δ as a function of the magnetic course (*MC*).

The classical form of the equation is as follows:

$$\delta = \operatorname{arctg}\frac{A + B\sin MC + C\cos MC + D\sin 2MC + E\cos 2MC}{1 + B\cos MC - C\sin MC + D\cos 2MC - E\sin 2MC} \tag{2}$$

Here A, B, C, D, E – deviation factors. These coefficients are functions of terrestrial magnetism and the magnetic forces that depend on the parameters of ship iron – λ.

$$A = \frac{d-b}{2\lambda};\; B = \frac{P+cZ}{\lambda H};\; C = \frac{Q+fZ}{\lambda H};$$
$$D = \frac{a-e}{2\lambda};\; E = \frac{d+b}{2\lambda} \tag{3}$$

where:

H – horizontal component of the force of terrestrial magnetism;
P – longitudinal forces of the permanent magnetism of the vessel;
Q – transverse forces of the permanent magnetism of the vessel;
a and e – Parameters of the symmetrical longitudinal and transverse magnetic soft iron;
b, c, d, f – Ship options of asymmetrical soft iron;
$\lambda = 1 + (a + e)/2$ – Factor of the direction force λH.

A simplified formula of the deviation at small angles as a function of the compass course (*CC*) is:

$$\delta = A + B\sin CC + C\cos CC + D\sin 2CC + E\cos 2CC \tag{4}$$

This deviation formula contains three specific components.

Constant component – (factor A) does not depend on the course and is offset by simple reversing of the flux to the appropriate angle.

Semicircle deviation ($B\sin CC + C\cos CC$) offset by the fore-and-aft and lateral magnets for adjustment.

Quadrantal deviation ($D\sin 2CC + E\cos 2CC$) is offset by spheres or bars made from soft iron.

Heeling deviation

In addition to semicircular, quadrantal, and constant deviation, the compass may have a heeling deviation, due to oscillations in roll or pitch, which is described (Kozhukov, Vorov & Grigoriev, 1971; Handbook, 2004) by the expression:

$$\delta = \left(\frac{R}{\lambda H}\sec I + \frac{(e-k)Z}{\lambda H}\tan I\right)\theta\cos CC \tag{5}$$

where:

Z – vertical component of terrestrial magnetism;
R – vertical component of the permanent magnetism of the ship;
I – magnetic inclination;
θ – angle of the vessel heeling over.

Separate compensation for this type of deviation on seagoing vessels presents special difficulties and runs in two different positions with significant difference of navigational latitude (20° and more).

Deviation from induction

Deviation from induction is caused by the proximity of the quadrantal correctors of the magnetic compass system.

For this reason, in addition to the impact of the Earth's magnetic field, a corrector acquires additional magnetism induced by the magnetic compass system itself.

This extra magnetism causes deviation. The magnitude of this deviation (Smirnov, Ialovenko & Perfiliev, 2000; Smirnov, 2004) is given by:

$$\delta = \frac{V\mu_0(æ_x - æ_y)M}{8\pi^2 r^6 \lambda H}\sin CC \tag{6}$$

where:

$æ_x$ – magnetism of the corrector for the XX axis;
$æ_y$ – magnetism of the corrector for the YY axis;
M – magnetic moment of the compass;
V – quantity of the corrector;
μ_0 – magnetic permeability of a vacuum $\mu_0 = 4\pi\cdot 10^{-7}$ [N/A^2];
r – distance from the center of the compass to the center of the corrector.

The main factors of deviation

Of all the types of deviation, the semicircle deviation is characterized with the highest value and the greatest instability, depending on the forces P and Q. These forces are stable until the first roll of the ship. The semicircle deviation is the main reason for systematic deviation-related work.

Usually, the adjustment of the deviation within the range required by the regulations takes the adjuster two to four hours and is costly.

Nowadays, when the role of the magnetic compass has been reduced to a backup device fitted "*just in case*", additional care requires time and money to maintain its accuracy and this does not make seafarers nor shipowners enthusiastic about it. From this perspective, the maintenance costs of the gyrocompass and GPS (instruments of paramount importance) are much lower.

A satisfactory solution to this problem can only be provided by such a decision which results in the magnetic compass not requiring any deviation adjustment.

This idea may seem rather bold, but it is both realistic and appropriate.

All kinds of deviation – semicircle, quadrantal, constant or heeling, deviation from induction, electromagnetic deviation, and other types of deviation depend on the compass direction force λH.

The horizontal component of terrestrial magnetism depends only on the latitude and it cannot otherwise be affected. The coefficient λ of the compass force is defined by the expression:

$$\lambda = 1 + \frac{a+e}{2} \tag{7}$$

In a typical installation and rigging of the compass, the steel elements affect the adjustment of deviation (Kozhukov, Vorov & Grigoriev, 1981). The coefficient λ on the bridge is usually found to be within 0.9–0.8, and in the wheelhouse within 0.7–0.5. The smaller coefficient λ is the reason for the smaller sensitivity of the compass and a greater deviation.

By setting the compass with compensatory iron with positive options *a* and *e*, it is possible to increase the parameter λ, and thus reduce all types of deviation.

It is possible and necessary to not struggle with separate types of magnetic compass deviation, as it has been the case until now, but simultaneously with all the deviations.

The coefficient of guiding force λ can serve as a universal means to eliminate all sorts of deviation.

Analysis of the dependence of the factor *λ* on the parameters of type *a* and *e* soft magnetic correctors

Soft iron magnetic ship components *a*, *b*, *c*, *d*, *e*, *f*, *g*, *h*, *k* are defined (Kozhukov, Vorov & Grigoriev, 1971) by the formulas:

$$a = \chi_X \frac{\partial_V^2}{\partial_X^2}; \quad b = \chi_Y \frac{\partial_V^2}{\partial_X \partial_Y}; \quad c = \chi_Z \frac{\partial_V^2}{\partial_X \partial_Z}$$

$$d = \chi_X \frac{\partial_V^2}{\partial_X \partial_Y}; \quad e = \chi_Y \frac{\partial_V^2}{\partial_Y^2}; \quad f = \chi_Z \frac{\partial_V^2}{\partial_Y \partial_Z}$$

$$g = \chi_X \frac{\partial_V^2}{\partial_X \partial_Z}; \quad h = \chi_Y \frac{\partial_V^2}{\partial_Y \partial_Z}; \quad k = \chi_Z \frac{\partial_V^2}{\partial_Z^2} \tag{8}$$

where:

χ_X – magnetism of a body along the XX axis of the ship;

χ_Y – magnetism of a body along the YY axis of the vessel;

χ_Z – magnetism of a body along the ZZ axis of the vessel;

∂_V – the differential of magnetic force *V*;

∂_X – component of coordinate along the XX axes;

∂_Y – component of coordinate along the YY axes;

∂_Z – component of coordinate along the ZZ axes.

For the present considerations the most interesting is the option with parameters *a* and *e*. The parameters *a* and *e*, for example, are simple correctors in the shape of a sphere of radius (*R*) at a distance (*r*) from the center of the compass which is situated in the plane of a frame ($x = 0$), and are described (Kozhukov, Vorov & Grigoriev, 1971; 1981) as follows:

$$a = -k\frac{R^3}{r^3}; \quad e = 2k\frac{R^3}{r^3} \tag{9}$$

where: *k* – the coefficient of the form.

The coefficient of the form *k* for a sphere is calculated by the formula:

$$k = \frac{\frac{4}{3}\pi\chi}{1 + \frac{4}{3}\pi\chi} \tag{10}$$

The parameters *a* and *e* of the same sphere situated in the plane of the center line ($x = r$) are described as:

$$a = 2k\frac{R^3}{r^3}; \quad e = -k\frac{R^3}{r^3} \tag{11}$$

where: χ – Poisson parameters which characterize the ship's magnetically soft iron, its magnetic quality and the shape and size, as well as the relative location of the origin in the center of the compass.

It can be seen from these expressions that the parameters *a* and *e* depend on a cubic correlation from the sphere radius *R* and the distance *r* of the sphere from the center of the compass.

This means that the reduction of the distances *r* between the spheres and the compass ball decrease for both coefficients by a factor of eight: *a* and *e*. The same can be said about the increase in the radius of the globe *R*.

This dependence allows us to achieve the desired effect by increasing the coefficient λ.

It should be noted that no one in modern science has carried out such an analysis. For this reason, in the last decade soft iron spheres have almost disappeared from everyday use. Instead of using a ball to compensate for the *D* factor, a longitudinal thin plate has been used.

A comparative analysis of the forces affecting the compass caused by the ships iron and by iron of correctors of type *a* and *e*

The total value of the parameters ($a + e$) on ships usually has a negative value. In this case, as mentioned above, on the main bridge of a ship the coefficient $\lambda = 0.9–0.8$ and on the wings $\lambda = 0.7–0.5$. From the formula of the coefficient λ you can calculate the total option ($a + e$), corresponding to these values. In the specified limits Table 1 shows the value of the coefficient λ as a function of the total ship setting ($a + e$).

Table 1. Dependence of (λ) on negative ship setting ($a + e$)

The total value of the parameter (a+e)	The value of the coefficient λ
−1.0	0.5
−0.8	0.6
−0.6	0.7
−0.4	0.8
−0.2	0.9
0.0	1.0

It can be seen that the relationship is linear in nature. The greater the negative value of the total parameter ($a + e$), the smaller the coefficient λ will be and therefore the accuracy of the compass that depends on it.

However, we can choose the iron correctors so that the total parameter ($a + e$) of this iron will be positive and have a large value. The coefficient λ can be increased by many times in this way. Such dependence has been presented in Table 2.

Table 2. Dependence of (λ) on the total positive parameter ($a + e$)

The total value of the parameter (a+e)	The value of the coefficient λ
−0.0	1.0
+1.0	1.5
+2.0	2.0
+3.0	2.5
+4.0	3.0
+5.0	3.5

The comparison of the data in Tables 1 and 2 shows that the positive influence of the correctors ($a + e$) can repeatedly exceed the negative impact of soft iron. In other words, the expansion joints type ($a + e$) here can be like a strong reception antenna, which multiplies the force guide λH of the compass.

Experiments at Szczecin Maritime University were made on the basis of an available deviascope.

First, only a magnet was installed to simulate the ship's magnetism. Measurements of the deviation were made on four cardinal point courses N, E, S, W and four intermediate courses NE, SE, SW, and NW. The results of the measurements have been presented in Table 3.

Table 3. Monitoring deviations on 8 courses in the absence of bars

MC [deg]	*CC* [deg]	δ [deg]
000	008	−8
045	046	−1
090	084	6
135	126	8
180	173	6
225	224.5	0.5
270	274	−4
315	321	−6

From the information in Table 3 the coefficients of deviation *A*, *B*, *C*, *D*, and *E* can be calculated. It is evident that the coefficients of a semicircle deviation *B* and *C* are of the greatest interest. These coefficients were calculated by the formulas:

$$B = \frac{\delta_{\mathrm{E}} - \delta_{\mathrm{W}}}{4} + \frac{\delta_{\mathrm{NE}} - \delta_{\mathrm{SW}}}{4}\sin 45° + \frac{\delta_{\mathrm{SE}} - \delta_{\mathrm{NW}}}{4}\sin 45°$$
$$C = \frac{\delta_{\mathrm{N}} - \delta_{\mathrm{S}}}{4} + \frac{\delta_{\mathrm{NE}} - \delta_{\mathrm{SW}}}{4}\sin 45° - \frac{\delta_{\mathrm{SE}} - \delta_{\mathrm{NW}}}{4}\sin 45° \tag{12}$$

Coefficient $B_1 = 5.7°$, and coefficient $C_1 = (-6.3)°$.

After these measurements, four bars of soft magnetic iron were additionally installed along the main axes XX and YY of the deviascope. The observations of deviations were made on the same courses and the results have been presented in Table 4.

The coefficients of the semicircle deviation *B* and *C* were also calculated by the formulas (12). Coefficients $B_2 = 2.5°$, $C_2 = (-2.4)°$.

The relation (N) of the semicircle deviations in the first and second variant characterizes the efficiency of the method:

$$N = \frac{B_1}{B_2} \approx \frac{C_1}{C_2} = \frac{\lambda_2}{\lambda_1} = 2.5 \tag{13}$$

Table 4. Monitoring of deviations on 8 courses with bars of soft iron installed

MC [deg]	*CC* [deg]	δ [deg]
000	004	−4
045	043.5	1.5
090	087	2
135	132	3
180	178	2
225	225	0
270	272.5	−2
315	320	−4

Measurements made with soft iron showed that a semicircle of deviation was reduced by 2.5 times. This means the reduction of the coefficient $\lambda - 2.5$ times and this correction makes the total deviation fall inside the limits that are deemed acceptable by the Regulations.

In comparison with the ordinary role of the coefficient λ on the ship ($\lambda = 0.8–0.9$), the increase in sensitivity was almost threefold. Such a result can already be considered as sufficient to solve the problem, even if there still is a possibility of an increase in the coefficient λ.

Extra bars placed on the intermediate axes between XX and YY of the vessel provide an additional opportunity to improve the efficiency of this method.

It should also be noted that at close distances to the compass, the setting of spheres or bars requires their accurate installation on the axes of symmetry. Over short distances, even small asymmetry in the fixing iron elements will lead to the appearance of unwanted additional parameters b, d, g, and h.

The last statement shows that the operation in this direction exceeds the capabilities of the adjuster and the crew members. Specific designs taking account of the soft iron fixing elements must already be developed in the compass production phase and their calibration should be a special task for the designers. Contemporary industrial enterprise has the capabilities to make a standard suspension device from soft magnetic iron of high quality (with the largest positive and identical parameters a and e).

Today, when science offers opportunities for operating at the molecular level (storing gigabytes of information in one cubic centimeter) such a task is feasible.

The herein proposed procedures are as follows: first at the initial installation of the compass the semicircle deviation is compensated by means of longitudinal and transverse magnets, which radically reduces all other deviations. Such adjustment would be applicable for the entire service life of the vessel.

A technically perfect production would take away all the problems and difficulties by manufacturing “deviation absorbent” compasses.

Conclusions

Attempting to separately eliminate a large number of different deviations of the magnetic compass is a losing battle. Identifying all new types of deviation in modern conditions is absolutely not superfluous and unnecessarily absorbs the time and attention of navigators.

A magnetic compass’ error should be determined at least once a watch while the vessel is at sea and, when possible, after any major alteration of course. The observed error should be recorded in the logbook. Checking the compass deviation regularly may indicate the need for repair, testing, or adjustment. In addition, compasses should be inspected occasionally by a competent officer or compass adjuster (Resolution A.382(X), 2009).

It was decided to verify how the compliance requirements that are related to the operation of magnetic compasses and gyrocompasses look in practice.

For this purpose, the survey was conducted in two ways. Firstly the survey was conducted among the captains and chief officers; secondly extracts from dozens of ships’ logbooks were analyzed. The average length of service for a marine survey was 17 years.

It should be noted that only 28% of the respondents set the gyro in accordance with good sea practice and regulations, at least once a watch. Given this fact and the fact that 56% of respondents determined the corrections of the magnetic compass by comparing it with the gyrocompass, it can be concluded that only about 20% of the officers did that in accordance with the regulations for controlling the magnetic compass (Pleskacz, 2017).

To verify these results, the authors analyzed 24 logbooks from commercial vessels operating under various flags.

In order to know the actual state of the course control indicators on the ships of the world fleet, records of 37 log-books from 17 different countries were analyzed (Pleskacz, 2017). Copies of the logbooks were delivered by the captains of ships calling at Szczecin Port.

All the vessels from which information has been obtained were merchant ships flying different flags and manned by crews from different countries. Randomly selected entries were chosen from five consecutive days when the ships were in operation on the open sea or on the approach to the port. A total of 2631 individual entries in logbooks were examined. The term “single entry” means records relating to a single, specific hour of observation, which is a single line entry in the log book.

Statistical processing of the data from the logbooks led to surprising results. It was found that 100% of the true courses obtained from a gyrocompass and a magnetic compass written down in the examined logbooks had exactly the same values.

The results of the analysis of the logbooks were compared with the results of actual tests conducted on 35 ships navigating the mouth of the Oder. As a result of the implementation of the cognitive objective, an experiment was conducted reading values of courses in operating conditions when the helmsman steered exactly in the line of leading. It was found that the mean square deviation of the difference between the true course specified using a magnetic and gyro compass for the statistical average vessel was: $m_{\Delta TC} = \pm 2.0^{\circ}$ instead of zero, as always entered in the logbooks (Pleskacz, 2017).

In such a situation, the question about the causes of this state of affairs inevitably arises.

In order to understand and respond to such formulated questions a detailed analysis of the practices of filling in logbooks, as compared to the real requirements for the officers of the watch, the content of training and stereotypes negatively changing good sea practice should be made.

The proposed approach allows this problem to be radically solved – once and for all.

It is particularly important that this task be solved not on a ship but in a land-based factory. The technical progress of recent years allows for the elimination of these problems and difficulties that appeared several decades ago.

Implementation of this research is very importance; therefore it should be given appropriate attention and support on the part of ship owners, seafarers, and the IMO, in terms of technical implementation and regulatory instruments.

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References

1. Bowdwitch, N. (2017) *American Practical Navigator*. USA: National Geospatial-Intelligence Agency.
2. Denne, W. (1979) *Magnetic Compass Deviation and Correction : A Manual of the Theory of the Deviations and Mechanical Correction of Magnetic Compasses in Ships*. Glasgow, UK: Brown, Son & Ferguson Ltd.
3. Handbook (2004) *Handbook of Magnetic Compass Adjustment*. National Geospatial-Intelligence Agency, Washington, D.C.: Defense Mapping Agency Hydrographic/Topographic Center [Online] Available from: https://msi.nga.mil/MSISiteContent/StaticFiles/HoMCA.pdf. [Accessed: February 10, 2018]
4. IMO (2004) *The International Convention for the Safety of Life at Sea.*
5. Jurdziński, M. (2014) *Deviation and compensation of marine magnetic compasses*. Gdynia: Gdynia Maritime University.
6. Kozhukov, V., Vorov, V. & Grigoriev, V. (1971) *Deviation of the magnetic compass*. Moscow: Publishing House “Transport” (in Russian).
7. Kozhukov, V., Vorov, V. & Grigoriev, V. (1981) *Magnetic compasses*. Moscow: Publishing House “Transport” (in Russian).
8. Łusznikow, E. (2010) *Deviation of magnetic compass*. USA: LULU.
9. Łusznikow, E. & Dzikowski, R. (2012) *Deviation of the magnetic compass*. Szczecin: Maritime University of Szczecin.
10. Łusznikow, E. & Pleskacz, K. (2012) Analysis of problems related to the use of ship’s course indicators. *Scientific Journals, Maritime University of Szczecin* 29(101), pp. 122–125.
11. Łusznikow, E. & Pleskacz, K. (2016) An analysis of practices of monitoring the accuracy and reliability of compasses on modern merchant ships. *Scientific Journals of the Maritime University of Szczecin, Zeszyty Naukowe Akademii Morskiej w Szczecinie* 45(117), pp. 174–180.
12. Łusznikow, E. & Pleskacz, K. (2017) *Contemporary considerations of change regulations regarding use of magnetic compasses in the aspect of the technical progress*. 12th International Conference on Marine Navigation and Safety of Sea Transportation TransNav, Gdynia.
13. Pleskacz, K. (2017) Necessity for a change to the control procedures for merchant vessel course indicators. *Scientific Journals of the Maritime University of Szczecin, Zeszyty Naukowe Akademii Morskiej w Szczecinie* 49 (121), pp. 69–74.
14. Regulations (1981) *Regulations by conventional equipment of sea ships*. Petersburg: “Transport” (in Russian).
15. Resolution A.382(X) (2009) *Magnetic compasses carriage and performance standards*. London: IMO.
16. Ron, D. (2009*) Magnetic deviation: Comprehension, compensation and computation* (*Part II*). [Online] Available from: http://myreckonings.com/wordpress/2009/04/18/magnetic-deviation-comprehension-compensation-and-computation-part-ii/ [Accessed: February 10, 2018]
17. Smirnov, E. (2004) *Marine navigation technique*. Petersburg: ELMOR (in Russian).
18. Smirnov, E., Ialovenko, A. & Perfiliev, V. (2000) *The technical means of navigation*. Petersburg: ELMOR (in Russian).
19. Vorov, V., Grigoriev, V. & Ialovenko, A. (2004) *Magnetic compasses*. Petersburg: Elmore Publishers (in Russian).