REPUBLIC OF AZERBAIJAN

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ABSTRACT

of the dissertation for the degree Doctor of Philosophy

PROPERTIES OF USEING A MAGNETIC LEVITATION SYSTEM IN MEASURING THE TECHNOLOGICAL PARAMETERS ON A SHIP

Specialty: 3319.01 - "Shipping techniques"

Field of science: Technical sciences

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Baku - 2025

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GENERAL CHARACTERISTICS OF THE WORK

Relevance of the topic and degree of devolepment. In the modern era, rapid advancements in scientific, technical, and technological fields have necessitated the development of more sophisticated devices and equipment. This, in turn, has expanded their areas of application and accelerated theintegration of new,promising technologies across various sectors.In this context, the present dissertation highlights the application of magnetic levitation systems in measurement technology as one of the current and relevant research directions.

It is well known that in the era of continuous scientific and technological progress,special attention is given to the development and implementation of innovative technical tools that meet the requirements of modern technologies across all areas of production. From this perspective, the development of existing and fundamentally new control devices emerges as a crucial issue. Among such devices, magnetic levitation (ML) systems-also known as magnetic suspensions that operate based on the principle of electromagnetic levitation hold a special place. One of the unique features of these systems is their ability to create a localized weightlessness condition, meaning that the magnetic core placed inside the solenoid remains in a levitated state. This property of magnetic levitation systems enables the design of highly sensitive and precise instruments.

Various methods of technical levitation have been in use for a long time and have gained increasing relevance with the advancement of technology. Magnetic levitation (ML) devices are widely used across different sectors of industry and technology. Since the levitating object is not in mechanical contact with the components of the measuring chamber, friction is virtually eliminated. A range of instruments operating on the principle of magnetic levitation has been developed, including automatic analytical balances, aerodynamic tunnel-type ML systems, devices for measuring the humidity of gases and dispersed materials, magnetic levitation inertial navigation systems, dosimeters, dust meters, vertical speedometers, and others.

Measuring the liquid level in the tanks and of oil tankers on ships is one of the important issues.Various types of level meters exist, and their advantages and disadvantages have been examined in the dissertation work. The main objective of this research is the development of a level measuring device based on the magnetic levitation principle for measuring technological parameters.

Despite the scientific and practical significance of numerous studies on the use of magnetic levitation systems in measuring technological parameters on ships, the application of buoy-type level meters for measuring liquid levels in the tanks of oil tankers, as well as their potential use in various reservoirs, has not been thoroughly and comprehensively investigated. Since these issues are the focus, the topic **of this dissertation is highly relevant**.

Object and subject of research. The object of the research is to carry out measurements in ship steam boilers and oil tanker tanks using an innovative measuring device based on the magnetic levitation principle with a wide measurement range. The subject of the research is the methods of measuring the liquid level (the volume portion filled with liquid) and density in various reservoirs using a magnetic levitation-based buoy-type level gauge.

Goal and tasks of the research. The purpose of the research is to investigate the application features of the magnetic levitation system in measuring technological parameters on ships, to develop a new-generation buoy-type level gauge based on the principle of magnetic levitation, and to address its implementation in measuring the liquid level in the tanks of liquid cargo vessels.

The main **objectives of the research are:**

1. Development of the structural diagram of a magnetic levitation device (MLD) designed to measure the level and density of a liquid in accordance with the specified requirements;
2. Determination of dynamic equations of forces affecting the magnetic levitation unit,which measures the level and density of fluid;
3. Determine the value of the constructive parameters of the magnetic levitation unit by measuring the level and density of the fluid;
4. The study of the stability of magnetic drinks on the basis of the mathematical model of the MLS;

5. Determination of measurement error and range based on experimental results by designing the measurement scheme of a magnetic levitation device for liquid level and density measurement;

6. Development of the principle electrical circuits of the leveling device, based on the principle of magnetic levitation;

7. Investigation of the laboratory prototype of a magnetic levitation device for measuring the level and density of a liquid, and analysis of the results;

8.Writing software that provides algorithm of device operation.

Investigation methods. The research has been carried out using theoretical studies,the theoretical methods of automatic control systems, the fundamental laws and methods of probability theory, mathematical statistics, and information-measurement systems theory, as well as by employing modern computer science, computational technologies, and software tools.

Basic provisions for defense:

1. Development of a magnet levitation system (MLS) based on the scientifically and methodologically substantiated temperature compensation of the induction of the levitating magnetic core;

2. Mathematical model of the corrected magnetic levitation system, analytical performances from its solution;

3. Magnetic hanging method and the functional scheme of the device based on this method, which is more effective than the methods currently used in measuring devices, with their sensitivity, accuracy and wide range of measurements;

4. The results of the constructive (design) parameters of the level measurement device and the developed structural diagram;

5. Development of the principal electrical circuit and software implementation of the buoy-type level measurement device;

6. A new-generation buoy-type monitoring and measurement device operating based on the principle of magnetic levitation for measuring liquid density and level.

Scientific novelty of the research: The results of the dissertation consist of the following scientific novelties:

1. Development of a next-generation buoy-type level measuring device based on magnetic levitation, offering a wide measurement range for monitoring technological parameters;

2. A new galvanomagnetic - type magnetic levitation system (MLS), identified as the most suitable solution for the implementation of magnetic suspension schemes, has been proposed;

3. A mathematical model of the MLS has been formulated in the form of the transfer function of a closed-loop system for the automatic control of solenoid current;

4. Analytical expressions have been obtained that establish the relationships between the parameters of the MLS and allow determination of its stability boundaries;

5. Development of the schematic diagram of a magnetic levitation device for measuring liquid level and density; investigation of the capabilities for measuring liquid level and density in various reservoirs using a magnetic levitation buoy-type level sensor (**Patent№ AR İ2017 0035**).

Theoretical and practical significance of research. The measurement of liquid levels in various tanks, including those of oil tankers, is one of the critical issues in marine applications. In this context, the development of a new type of buoy-type level gauge based on the magnetic levitation (ML) principle characterized by high accuracy, sensitivity, and a wide measurement range and its application in marine engineering is of significant practical importance. Additionally, the absence of inertia during operation, elimination of temperature-related errors, and the exclusion of mechanical contacts and springs allow the device to provide information in the form of an electrical signal.

Research validation and application. On the topic of the dissertation, 1 patent for an invention, 24 scientific works published in scientific journals and in collections of several conferences, including 6 sole-author articles, have been produced, of which were (2 - "Impact Factor," 1-Web of Science, 3- "Scopus," 2 - "Copernicus"). published in international databases.

For the float-type level measuring device prepared in accordance with the dissertation work, a patent has been granted for application in the measurement of liquid levels in ship steam boilers, tankers, and open and closed reservoirs. The description of the patented invention was recorded in the registry on 17.07.2017 under number İ2017 0035 by the Public Legal Entity and based on the analyses and materials conducted by the Intellectual Property Agency of the Republic of Azerbaijan in 2020, it has been included in the list of patents in force in Azerbaijan. It has been included in the teaching program of the subject “Electrical Measurements and Devices” and implemented in the teaching process. The results of the dissertation, work have been accepted for application by the Zigh Ship Repair and Construction Plant of “ Azerbaijan Caspian Sea Shipping” CJSC, as well as by the “Shamakhi” vessel of the same company.

The main results of the dissertation have been **presented and discussed at the following scientific-technical seminars and conferences**:

- "The 9th International Scientific-Technical Conference dedicated to the 91st anniversary of the National Leader Heydar Aliyev's birth.", Baku, ASMA, 2014.;
- "The International Scientific-Technical Conference on Problems of Metallurgy and Materials Science", Baku, AzTU – 2016.;
- "The 20th Republican Scientific Conference of Doctoral Students and Young Researchers organized by the Ministry of Education, Baku, ASOIU – 2016.";
- "The 13th. and 15th. International Scientific-Technical Conferences dedicated to the 95th and 97th anniversaries of the National Leader Heydar Aliyev's birth, Baku, ASMA - 2018, 2020."
- "International Scientific-Technical Conference of Admiral F. F. Ushakov Novorossiysk State Maritime University, Novorossiysk – 2020.";
- "International Conference on 'Cooperation of Science and Industry: Models, Systems, and Technologies', Kaluga – 2020.";
- "V International Scientific and Practical Conference on 'Global and Regional Aspects of Sustainable Development', International Scientific-Technical Conference, Copenhagen – 2021."

- "International Scientific-Technical Conferences on "Innovative Development Perspectives of Technical and Natural Sciences" held by the Department of Applied Mechanics, Baku, ASMA – 2021.;
- The 5th International Eurasian Risk Conference titled "Innovations in Minimizing Natural and Technogenic Risks" dedicated to the 100th anniversary of the National Leader Heydar Aliyev's birth, "RISK-2023 Conference", International Scientific-Technical Conference, Baku, ASMA - 2023.

Name of the organization where the dissertation was carried out. The dissertation was carried out at the "Ship Electro-Automation" Department of the "Azerbaijan State Marine Academy" Public Legal Entity.

Publication of the Research Results. The main propositions of the conducted research are reflected in 24works, including 10 articles in collections of international scientific conferences and 14 articles in journals listed by the Supreme Attestation Commission (including 2 articles abroad in Impact Factor, 2 articles in Copernicus, 1 article in Web of Science, and 3 articles in Scopus).

Personal contribution of the candidate in research. The relevance of the research has been substantiated by the applicant, the main objective has been defined, and the tasks set to achieve this objective have been formulated. The research has been conducted, and both theoretical and practical issues have been independently addressed. The results have been processed, systematized, and discussed. The submitted dissertation is a completed scientific research work, written personally by the applicant, encompassing a set of scientific, and practical propositions and findings put forward for defense.

Volume of the dissertation by structural sections and total character count. The dissertation consists of an introduction, four chapters, a conclusion, a list of 106 references, and appendices. The dissertation is described in 155 printed pages, including 2 tables and 49 figures. The total volume of the dissertation is 193230 characters (title page - 398 characters, table of contents - 5710 characters, introduction - 14709 characters, first chapter - 40080 characters, second chapter - 43619 characters, third chapter - 35473 characters, fourth chapter - 24433 characters, conclusion - 2496 characters).

THE MAIN CONTENT OF THE DISSERTATION

In the introduction, the relevance of the thesis topic and the extent to which the problem has been studied are substantiated. The object and subject of the research, the purpose and objectives of the study are defined. The research methods, main theses submitted for defense, scientific novelty of the work, practical and theoretical significance of the research, approbation of the research results, publication of the research, as well as the structure and volume of the work are presented.

In the first chapter, a literature review is presented. The theoretical and methodological aspects of measuring technological parameters on ships have been examined, including the interpretation of controlled parameters in the tanks of liquid cargo vessels, a comparative analysis of level-measuring devices and methods, the selection of an appropriate measurement approach, the determination of dimensions based on the statistical stability of the levitation element, and the justification for the use of the magnetic levitation principle in level measurement. The development of a new type of wide-range device, for measuring the level and density of liquids in the maritime field has emerged as one of the key challenges, leading to the creation of an innovative measuring instrument for the assessment of technological parameters.

Various devices based on the principle of magnetic levitation have been designed and developed, including automatic analytical balances, aerodynamic tube-model magnetic levitation systems, instruments for measuring the moisture content of gases, and dispersed materials, magnetic levitation-based inertial navigation systems, dosimeters, vertical velocimeters, dust concentration meters with magnetic suspension, buoy-type level gauges, and others.

As the precise, determination of the specific gravity of liquid cargo received by a ship is one of the most critical tasks, the structural diagrams, classifications, and characteristics of the Hermetic UTI 2000 device – used in maritime applications for level measurement - have been examined and comparatively analyzed. A generalized classification of devices utilizing the magnetic levitation principle has also been presented.

The principle of magnetic levitation offers numerous advantages. The operation of such devices is based on the balance of two forces - gravitational force and the electromagnetic force that maintains the object in a levitated state.

Among the devices mentioned above, the buoy-type level gauge, based on the principle of magnetic levitation, stands out due to its high accuracy, sensitivity, and wide measuring range. This device enables the measurement of both the level and density of liquids in various reservoirs. The levitating body, serving as the sensitive element, can be placed in different measuring chambers. During operation, the system benefits from the absence of inertia, thermal drift, and mechanical contact or springs, and allows for the acquisition of measurement data in the form of an electrical signal.

The theoretical and methodological aspects of measuring technological parameters on ships, along with the monitored parameters in oil tanker tanks, have been investigated. To address existing deficiencies, improvements have been proposed for previously developed devices, and the application of new methods and recent advancements in electronics has been emphasized. These improvements enable faster and more accurate execution of processes, while also meeting the high reliability demands of equipment used in marine environments. Consequently, the development of a new, wide-range device for measuring the level and density of liquids in the maritime sector has become a pressing and highly relevant issue.

In the second chapter, the application of magnetic levitation systems in measurement technology, the comparative analysis of magnetic levitation schemes,the influence of constructive parameters on the force characteristics of electromagnetic levitation systems, and certain theoretical aspects of levitation in electromagnetic systems with soft magnetic core materials have been investigated. It has been determined that studying, the selection of constructive parameters leads to more effective decision-making in the development of devices based on the principle of magneticlevitation.In the design of devices operating on the principle of magnetic levitation systems (SML), it is advisable to calculate the constructive parameters based on the predefined values of the magnetic core parameters.

In recent years, various schemes and methods have been investigated, and corresponding achievements have been made in the control of objects under the influence of magnetic fields.Numerous tests have been conducted and new configurations explored to enhance the efficiency of magnetic levitation. The magnetic core, serving as the sensitive element of a solenoid, has been successfully utilized as a transmitter in various measuring instruments and systems.

During the development and design of devices based on the principle of magnetic levitation, the determination and analysis of the interaction forces betweenthe magnetic fields generated by the magnetic core and the solenoid are of significant interest.

The electromagnetic attraction force of a solenoid with a hard magnetic core has been determined. A typical calculation scheme used to define the force characteristicsof the solenoid is presented in figure 1.

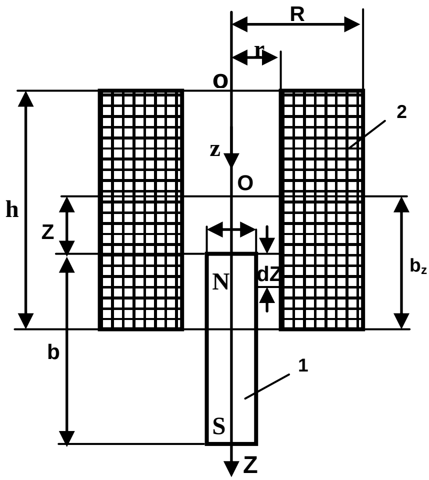

Figure. 1. Typical calculation scheme defining the strength characteristics of the solenoid

After calculating mathematical calculations, we will use the expression of the force of the solenoid:

$$F_э = \frac{\pi \cdot d_м^2}{8 \cdot d_п^2} \cdot B_м \cdot h \cdot K(\bar{z}) \cdot I_c = K_0 \cdot I_c \qquad (1)$$

Here $d_м$ - diameter of the magnetic core, м;

$B_м$ - magnetic induction on the axis of the material of the magnetic nucleus, Tl;

$K(\bar{z})$ - the coefficient $\bar{z}$ of the interaction force of the solenoid with the magnetic inlet as a function of the reading coordinates;

$$K(\bar{z}) = \bar{z} \cdot \ln \frac{\bar{R} + \sqrt{\bar{R}^2 + \bar{z}^2}}{\bar{r} + \sqrt{\bar{r}^2 + \bar{z}^2}} - (\bar{z} - 1) \cdot \ln \frac{\bar{R} + \sqrt{\bar{R}^2 + (\bar{z} - 1)^2}}{\bar{r} + \sqrt{\bar{r}^2 + (\bar{z} - 1)^2}} -$$
$$- (\bar{z} + \bar{b}) \cdot \ln \frac{\bar{R} + \sqrt{\bar{R}^2 + (\bar{z} + \bar{b})^2}}{\bar{r} + \sqrt{\bar{r}^2 + (\bar{z} + \bar{b})^2}} + (\bar{z} - 1 + \bar{b}) \cdot \ln \frac{\bar{R} + \sqrt{\bar{R}^2 + (\bar{z} - 1 + \bar{b})^2}}{\bar{r} + \sqrt{\bar{r}^2 + (\bar{z} - 1 + \bar{b})^2}}$$

Here

$$K_0 = \frac{\pi \cdot d_м^2}{8 \cdot d_п^2} \cdot B_м \cdot h \cdot K(\bar{z}) \qquad (2)$$

According to the results of the force characteristic calculations, it is possible to determine the most efficient suspension point of the magnet - i.e., the most effective levitation position - corresponding to the maximum current constant that ensures levitation while minimizing energy consumption.

Figure 2 shows the graphs of the dependence obtained based on calculations. As can be seen from the graph, the $K(\bar{z})$ coefficient is an extreme function.

Thus, the proposed method for determining the interaction force between the magnetic core and the solenoid allows for calculating the MLS parameters with sufficient accuracy, which is convenient when conducting research and experimental design work on devices based on the principle of magnetic levitation.

As a result, it was determined that the study of the selection of structural parameters leads to more effective decision-making in the design, of devices operating on the principle of magnetic levitation, and in the creation of devices operating, on the principle of MLS, it is advisable to calculate the structural parameters based on the given values of the parameters of the magnetic core.

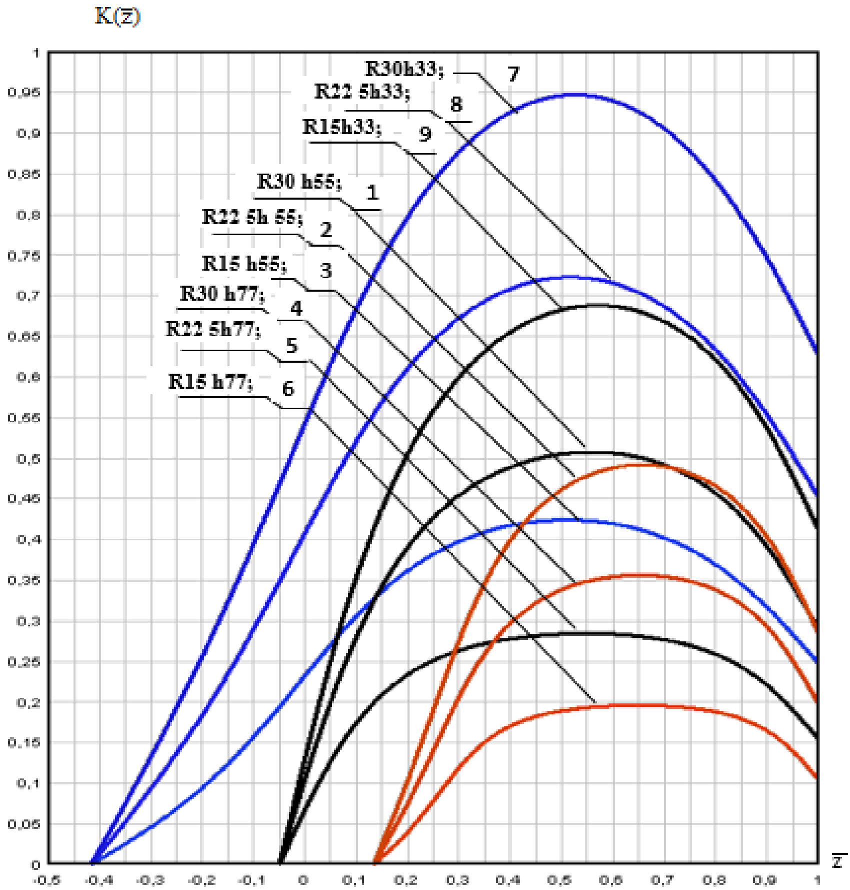

Figure 2. Also shows the graphs obtained based on the dependence calculation. b = 44 mm if h = 33, 55, 75 mm.; P = 33, 22.5, 15 mm.; r = 7 mm. = const

The following results were revealed from the conducted studies:

1. Some theoretical issues of levitation of soft magnetic nuclei in the electromagnetic system have been investigated, the magnetic fields of the solenoid and the methods of interaction of the levitating axis made of magnetic material are determined to be able to magnetize the arrows or material that can be absorbed into the solenoid. The calculations have shown that the electromagnetic force is generally proportional to the square of the solenoid current (up to the magnet) and also depends on the ratio of the arrow to the center of the solenoid.

2. Electromagnetic force of solenoid with solid magnetic material is assigned. It has been found that the strength characteristics depend on the coefficients and depend on the geometric parameters ($\bar{R}$, $\bar{r}$, $\bar{b}$) and the Z coordinate of the solenoid and magnetic resonance. The remaining quantities (μ_0, j_Z, S; h; $d_п$, I_c) play a role of scale production and do not exaggerate the characteristics and are of extreme character;

3. In the development of devices based on the principle of electromagnetic levitation, the selection of the most suitable (i.e., efficient, and functionally appropriate) parameters of the system's power components has emerged as one of the key scientific and practical challenges. From this perspective, the primary objective in investigating the force characteristics of the magnetic levitation system (MLS) is to determine the most favorable values of its key parameters in terms of energy consumption, control accuracy, and operational stability. Such parameters not only ensure a stable, and steady levitation regime but also reduce energy consumption, and facilitate the precise maintenance of the levitation current.

The third chapter describes the structural scheme of the magnetic levitation system, the determination of the transfer function of the individual elements, the mathematical model of the magnetic levitation system, the study of the stability of the magnetic levitation system, the structural scheme of the magnetic levitation system, the magnetic leverage. The problem of ensuring stable, and stable levitation of magnetic drinks has been solved by exploring its dynamic properties, determining the necessary, and sufficient conditions. The obtained results allow us to determine the best mode of operation of the MLS based on the stability, and stability of the dynamically corrected system. This magnetic levitation is a prerequisite for providing the necessary metrological characteristics on devices of the type. It should be noted that the results, of the developed MLS validations allow the most efficient selection of the key static, and dynamic system parameters. The figure depicts a galvanic magnet MLS scheme, with improved technical characteristics.

The typical electronic circuit of a galvanomagnetic-type magnetic levitation system (MLS) assembled with discrete components has certain drawbacks, which have been eliminated in subsequent designs. All transistors in the amplifier circuits (except the power transistor) have been replaced with integrated operational amplifier circuits. This significantly simplifies the electronic unit's circuit, improves its mass-dimensional characteristics, and facilitates both circuit tuning and the development of the electronic block.

To formulate the system equation, the performed functions were divided among individual elements, a functional diagram (see figure 2.) was developed, and the system's structural scheme was constructed, enabling the formulation of its mathematical model [4][1].

The unit consists of 1 voltage switch, 2 vertical position solenoids and 3 internal soap magnetic levers, 4 measuring chambers, 5 vertical displacement levers in vertical position, 6 Hollow element, 7 voltage controller of solenoid, 8 voltage block. device.

It consists of 7 operating blocks of solenoid, 9 and 10, and 2 К157УД1 operating amplifiers. The amplifier 10 output is connected to the base of the 11 KT803A power transistor, 2 volts of solenoid and R6 resistor are connected to the emitter circuit consistently, which output, is connected to the 8 volts of the solenoid.

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[1] Allahverdiyeva, A.T. Determination of the Electromagnetic Pulling Force of a Solenoid with a Hard Magnetic Core // Proceedings of the Azerbaijan Engineering Academy, International Scientific-Technical Journal, Vol. 11, No. 4, Baku, 2019, pp. 52–57.

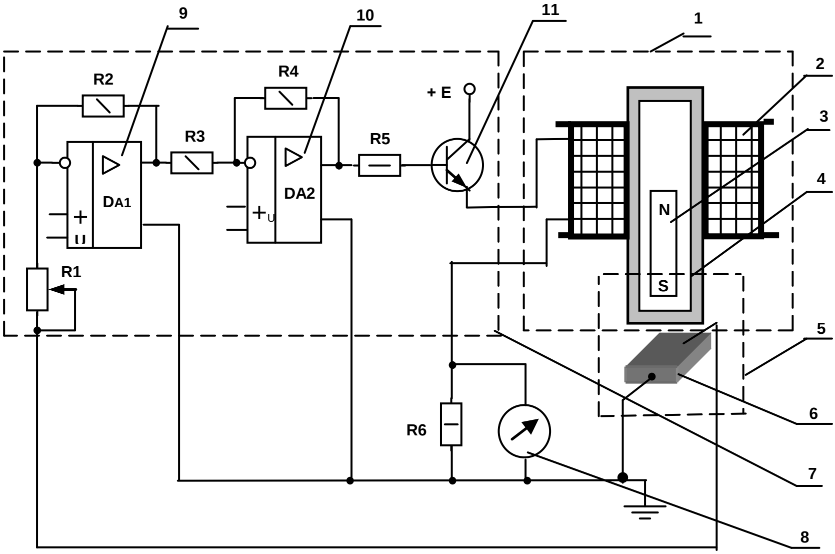

Figure 3. Basic electrical diagram of a galvanomagnetic type MLS

For the analysis of the interaction force between the solenoid, and the magnetic core equation 1, we apply the dynamic equilibrium equation of theforces acting on the magnetic core, disregarding external forces:

$$F_u + F_{ad} + F_e - G = 0 \qquad (3)$$

here

$$F_u = m.\frac{d^2Z}{dt^2}, \quad F_d = R_a.\frac{dZ}{dt}, \quad F_e = K_o.I_s \qquad (4)$$

The damping force F_d is determined by the resistance encountered by a body moving with velocity, dz/dt in a liquid or gaseous, medium and depends on the aerodynamic coefficient R_a.

It was determined that the damping force for a cylindrical linear measuring chamber is:

$$F_d = K_e \cdot \frac{8.\pi.\mu_c.b}{(n^2+1)-(n^2-1)/ln(n)} \cdot \frac{dZ}{dt} \qquad (5)$$

Here $К_e$ – is the eccentricity coefficient of the core 3 and the measuring chamber 4 axes.

In the system under study, the centering of the magnetic core is ensured by four shafts, which are perpendicular to the cylindrical surface of the core. For centered surfaces, $К_e = 1$.

μ_s – dynamic viscosity of the medium, $Н \cdot s/м^2$ (for air $\mu_s = 1.7 \cdot 10^{-5}$ $Н \cdot s/м^2$);

$n = d_k / d_s$ – is the coefficient of clearance between the surface of the measuring chamber 4 and 3;

(5) - we get from

$$R_a = \frac{8 \cdot \pi \cdot \mu_c \cdot b}{(n^2+1)-(n^2-1)/\ln(n)} \qquad (6)$$

The magnetic levitation system is characterized by auto-oscillations of the levitating body - the magnetic core - due to the fact that the automatic control system, of the solenoid current is a closed system. Such a magnetic levitation system has an unstable state. Based on the functional diagram of the magnetic levitation system (MLS), a corresponding block diagram (figure 4) has been constructed, which allows for the development of its mathematical model [80][2].

In the block diagram, the following symbols are used for the transfer functions of the respective components:

$W_0(s)$ – the transfer function of the force lines of the magnetic levitation system, which represents the placement of the magnetic core within the measuring chamber under the magnetic field of the solenoid.

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[2] Afandiyev, O.Z., Azizov, R.R., Allahverdiyeva, A.T. Investigation of the Dynamic Properties of Magnetic Levitation Systems, Admiral F.F. Ushakov State Maritime University // Operation of Maritime Transport, Novorossiysk, 2017, Collection No. 1 (82), pp. 37–41.

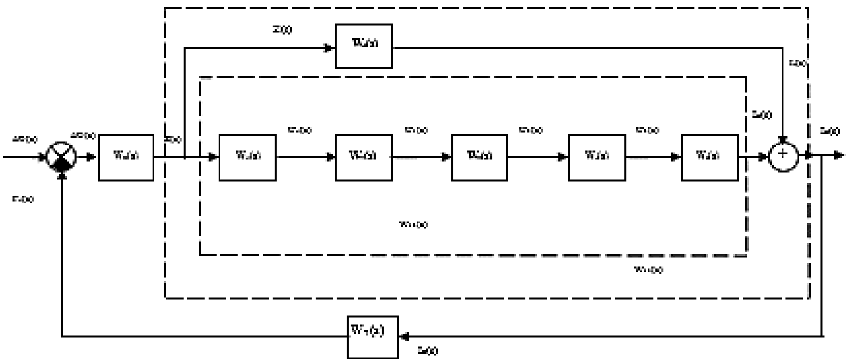

Figure 4. Structural diagram of MLS

The displacement of the insert Z_x creates a difference ΔG as a result of the difference between the magnetic gravity force G. and the electromagnetic attraction force F_e of the solenoid.

$$\Delta\mathbf{G} = \mathbf{G} - \mathbf{F_e} \tag{7}$$

$W_1(s)$ - the transfer function establishes a relationship between the output voltage U_x ,and the displacement Z_x of the Hall sensor.

$W_2(s)$ - the transfer function of the voltage amplifier establishes the relationship between the displacement sensor output voltage U_x ,and the voltage U_y generated at the amplifier output.

$W_3(s)$ - the transfer function of the second stage of the electronic amplifier block establishes the relationship between, the output voltage U_2 of the second stage, and the voltage U_1 of the first stage.

$W_4(s)$ - it is the transfer function of the voltage divider, which relates the voltage U_B at the transistor base to the voltage U_2 in the amplifier's second stage.

$W_5(s)$-the transfer function of the real part of the electromagnetic damping establishes the relationship between the current $\dot{\boldsymbol{I}}_{\boldsymbol{d}}$ which constitutes the dynamic component of the solenoid, and the displacement velocity of the core $\frac{\boldsymbol{dZ_x}}{\boldsymbol{dt}}$.

$W_6(s)$ - the transfer function of the feedback part, establishes the dependence between the electromagnetic attractive force F_e of the solenoid and the total current $\dot{I}_d$ of the solenoid. As a result of the continuous displacement of the magnetic core along the solenoid's axis, a self-induced electromotive force (EMF) is generated, in the solenoid winding, under the influence of which the current $\dot{I}_d$ flows.

$W_7(s)$ - the transfer function of the feedback part establishes the relationship between, the electromagnetic attractive force F_e of the solenoid and the total current $\dot{I}_s$ of the solenoid.

It should be noted that the results of the conducted research on the developed magnetic levitation system (MLS) enable the optimal selection of the system's main static and dynamic parameters. Therefore, the problem is formulated as follows: in order to ensure the stable position and steady levitation of the magnetic core, it is necessary to carry out both theoretical, and experimental investigations of the system's dynamic characteristics. To achieve this, a mathematical model of the studied system is required.

By performing the necessary mathematical operations

$$\boldsymbol{D}(\boldsymbol{s}) = \boldsymbol{a}_0 \,.\, \boldsymbol{s}^5 + \boldsymbol{a}_1 .\, \boldsymbol{s}^4 + \boldsymbol{a}_2 .\, \boldsymbol{s}^3 + \boldsymbol{a}_3 \,.\, \boldsymbol{s}^2 + \boldsymbol{s} = 0 \qquad (8)$$

we obtain it. By using the standard package of MathCAD software to find the roots of the specific mathematical equation, and by applying appropriate algebraic, and trigonometric transformations, we derive the final expression of the system's transient response function as follows:

$$\boldsymbol{I}_s(\boldsymbol{t}) = \frac{\boldsymbol{m.g}}{\boldsymbol{K}_0} .\left[1 + \boldsymbol{C}_2 \,.\boldsymbol{e}^{s_2 t} + \boldsymbol{C}_3 \,.\, \boldsymbol{e}^{s_3 t} + 2\boldsymbol{e}^{\alpha t} .\, (\boldsymbol{\delta}.\, \boldsymbol{cos}\,\boldsymbol{\omega t} - \boldsymbol{\sigma}.\boldsymbol{sin}\,\boldsymbol{\omega t})\right] \qquad (9)$$

The calculation and construction of the transient process make it possible to determine the system's dynamic error, which, in turn, will allow for the evaluation of the system's metrological characteristics during the measurement of technological parameters - characteristics that are subject to change, in the course of the process.

The function I_s (t) defines the transient response of the system under investigation. During the calculation of I_s (t) the error I_{sd} ($t_{sər}$), from the steady-state value should not exceed 1%. That is, we choose $\alpha \cdot t_{qr} = 5$;

Let us construct the transient response graph based on the calculation.

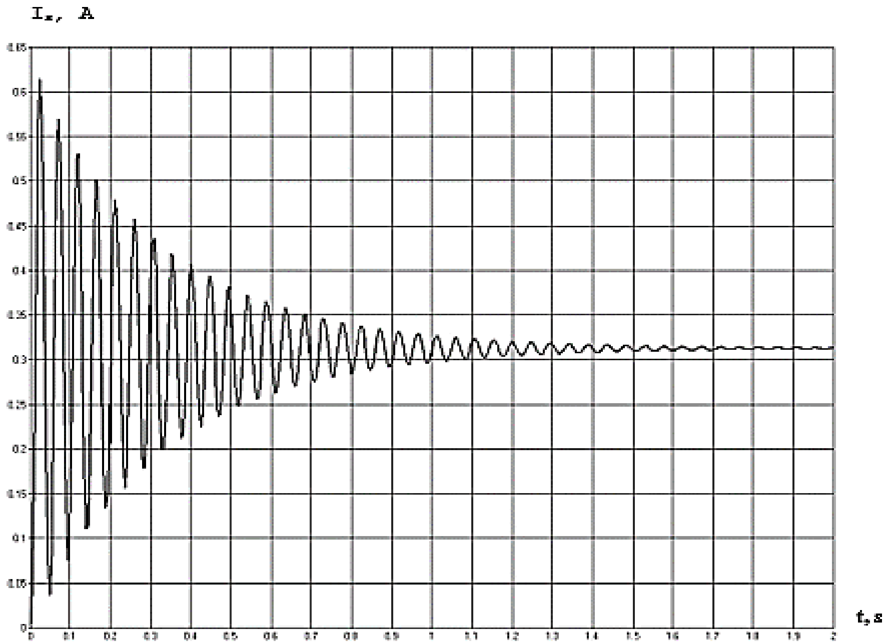

Figure 5. Transient response graph

Based on the graph (figure 5), let us evaluate the obtained results.

1. The response function $I_s(t)$, has an underdamped (oscillatory) nature; the damping point is

$$t_{max} = 0.025 \text{ мs.}$$

2. From the transient response graph, we determine the main dynamic quality indicators of the system.

- The maximum value of the response function (for the case tmax=0. (t_{max} = 0.025мs):

$$I_{s\,max} = 0.618 \text{ A}$$

- The steady-state value of the response function (when t_{set} = 2 seconds):

$$I_{s\ set} = 0.312\ A;$$

- Degree of regulation:

$$\frac{I_{smax} - I_{sqer}}{I_{sqer}}.100\% = \frac{0.618 - 0.312}{0.312}.100\% = 98\%;$$

- Impulse delay and duration with ≤ 1% error:

$$t_{3.p.i} = 1.6\ s;$$

- The oscillation frequency of the output quantity of I_s:

$$f = \frac{\omega}{2\pi} = \frac{133 rad / s}{6.28 rad} = 21.2\ Hs.$$

Since the system's natural frequency f=21.2 Hz, is relatively high, the levitating core and the levitation current are not visually observable, and the magnet quickly restores stability, ensuring a return to the levitation state.

As seen from the constructed transient process based on the report (figure 5), the damping time of the transient process is 1.8 seconds, and the number of oscillations is approximately 30. To achieve better control quality, the performance indicators can be improved by adding a Proportional-Integral-Derivative (PID) controller.

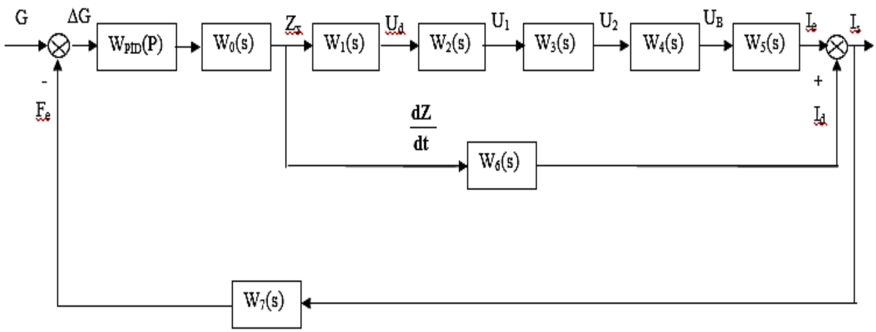

Figure 6. Structural diagram of the magnetic levitation system with an added PID controller

The mathematical model of the Proportional-Integral-Derivative PID controller is as follows:

$$U = K_p \varepsilon + \frac{1}{T_i}\int_o^t \varepsilon dt + T_d \frac{d\varepsilon}{dt}$$

Here, K_d, T_i, and T_d are the optimal tuning parameters of the controller, which are calculated using analytical methods. Taking these into account, the resulting transient process is shown in figure 7.

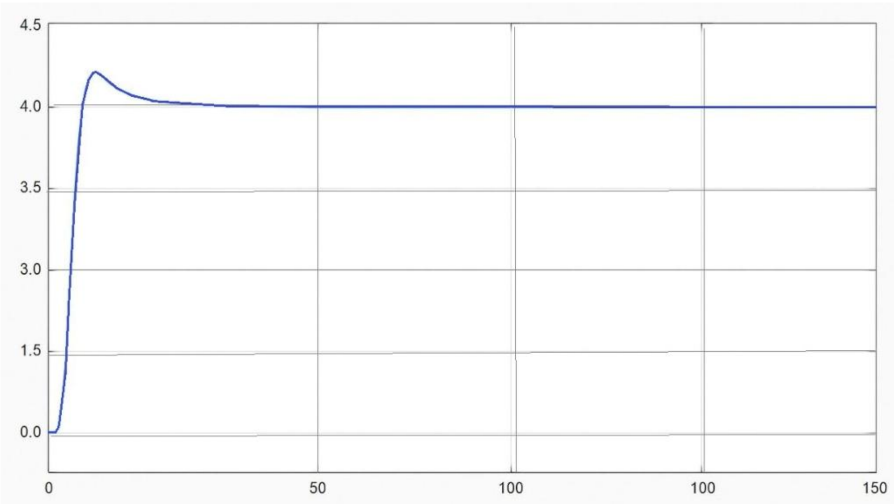

Figure 7. Graph of the transient process obtained by adding the PID controller

The results obtained can be used in the design of devices using a magnetic levitation system.

As seen from the transient response curve, the quality indicators of the transient process have improved. Specifically, the excessive regulation

$$\boldsymbol{\sigma} = \frac{x - x_0}{\boldsymbol{x}} 100\% = \frac{4{,}25 - 3{,}75}{3{,}75} 100\% = 13{,}3\%$$

regulation time

$$t_{з.р.i} = 0{,}5 \text{ s},$$

the number of oscillations is

$$\mu = 1$$

As is well known, the quality indicators of a control system are used to evaluate the effectiveness of the system's response and control performance, and they are determined based on the transient (step) response characteristics.Based on the results obtained from the transient response graph, it can be concluded that by adding a Proportional-Integral-Derivative (PID) controller, the vibrations in the system can be eliminated, and a high-quality transient process can be achieved. The Proportional-Integral-Derivative (PID) controller is widely used as a control algorithm in automatic control systems to improve the system output to the desired value, and maintain its stability.

Chapter Four the functional diagram of the magnetically suspended buoy-type level gauge device was developed, and the design and analysis of a buoy-type density and level measurement device based on the magnetic levitation principle were conducted. A buoy-type level, and density measurement device operating on the basis of magnetic levitation was studied.

The magnetically suspended buoy-type level gauge consists of a vertically oriented solenoid, a measuring chamber placed inside it, and a traction unit comprising levitating permanent magnets. The system is distinguished by the inclusion of a measurement unit for determining the liquid density, a buoy fixed to the levitating permanent magnets that serves as a sensitive element, a microcontroller, a level indicator, thermistors, mesh-type partitions made from non-magnetic material, and a galvanomagnetic transmitter associated with the permanent magnet, which is connected to the solenoid current control unit. The output signals from the measurement resistors are fed to other inputs of the microcontroller, with its output connected to the level indicator (Figure 8) [33][3].

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[3] Allahverdiyeva, A.T. Measurement of Liquid Properties Using a Magneto-Levitational Buoy-Type Level Gauge in Ship Tanks // V International Scientific and Practical Conference: Global and Regional Aspects of Sustainable Development, Copenhagen, Denmark, October 2021, No. 82, pp. 194–203.

The magnetic float level measuring device consists of two parts: I - the device measuring liquid density, and II - the device measuring liquid level. The function of the density sensor is to provide correction to the device during level measurement.

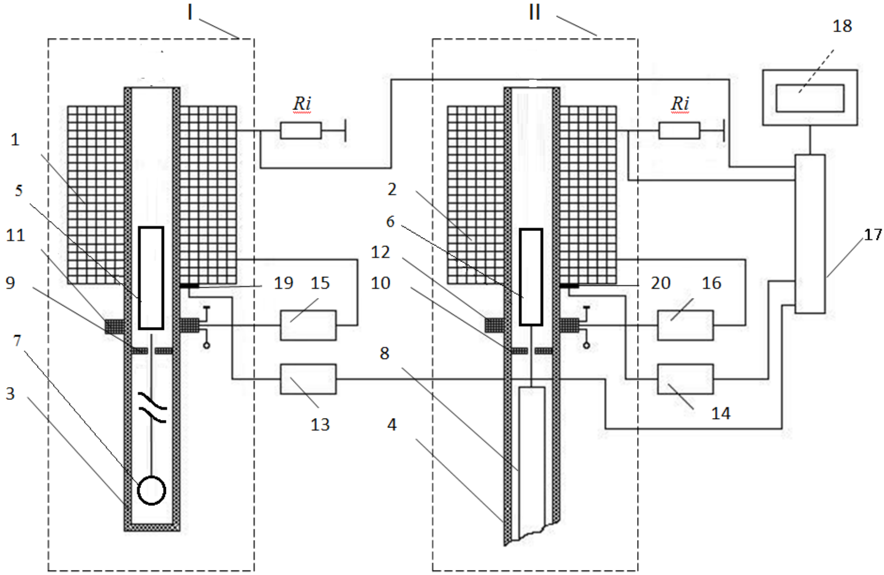

Figure 8. Scheme for measuring level and density of liquid gauge by means of magnetic levitation device and displacer

The operating principle of the float-type level sensor is based on Archimedes' principle. According to this principle, the weight of the float in the liquid changes proportionally to the change in the liquid level. When there is no liquid, the buoyant force does not act, and the float remains suspended in the air. In this case,

$$\rho_b = \frac{A}{R_a} U_m; \qquad \rho_m = 0 \tag{10}$$

Here, U_m - the maxsimum value of the voltage drop across the resistor R, corresponding to the current flowing through the coil of the electromagnet in the absence of liquid.

$$\rho_b - \rho_m = \frac{A}{R_a} U; \qquad \rho_m \neq 0 \qquad (11)$$

When there is liquid, the buoyant force acts and the float floats inside the liquid. In this case,

$$\rho_m = \rho_b - \frac{\rho_b}{U_m} \cdot U \qquad (12)$$

Here, U - a certain value of the voltage drop across the resistor R, which corresponds to the current flowing through the coil of the electromagnet when it is liquid.

U, U_m, ρ_b - knowing the value of - using the expression (12) ρ_l - the liquid density it can be determined.

After determining the liquid density ρ_m, the level of the volume filled with liquid can be measured using the float. With the help of the formulas obtained through transformations, the microcontroller continuously determines the quantities ρ\rhoρ (density), and θ\thetaθ (level) with high accuracy.

Considering these processes, by performing the necessary conversions on the analog voltage signals received at the microcontroller's PORT C.0 and PORT C.1 inputs, the following expressions are obtained to determine the density and level of the measured liquid:

$$\frac{U'}{U'_m} = 1 - \frac{\rho_m}{\rho_b} \cdot \frac{h}{H}$$

$$\theta = \frac{h}{H} = \frac{\rho_b}{\rho_m} \cdot \left(1 - \frac{U'}{U'_m} \right) \qquad (13)$$

In the schematic electrical diagram (figure 9.) RV1 and RV2 variable resistors serve to obtain a voltage from 0 to 5V, which corresponds to the current flowing through the electromagnets. These signals, which correspond to the density of the fluid and the filled part of the volume supplied to the terminals PC0 and PC1 (0 and 1 outputs of port of C) ATMEGA8 microcontroller. The button, the resistor R2 and the output PC6 are used to reset (command RESET) ATMEGA8 microcontroller. Port B (PB0 conclusions, PB1, PB2, PB4, PB5, PB6 and PB7) is used for the liquid crystal display LM016 to display the obtained results.

To verify the accuracy of the calculation results, a schematic electrical circuit (figure 9) was assembled using variable resistors, microcontrollers, and a liquid crystal display in the "Proteus 7 Professional" software environment [87][4].

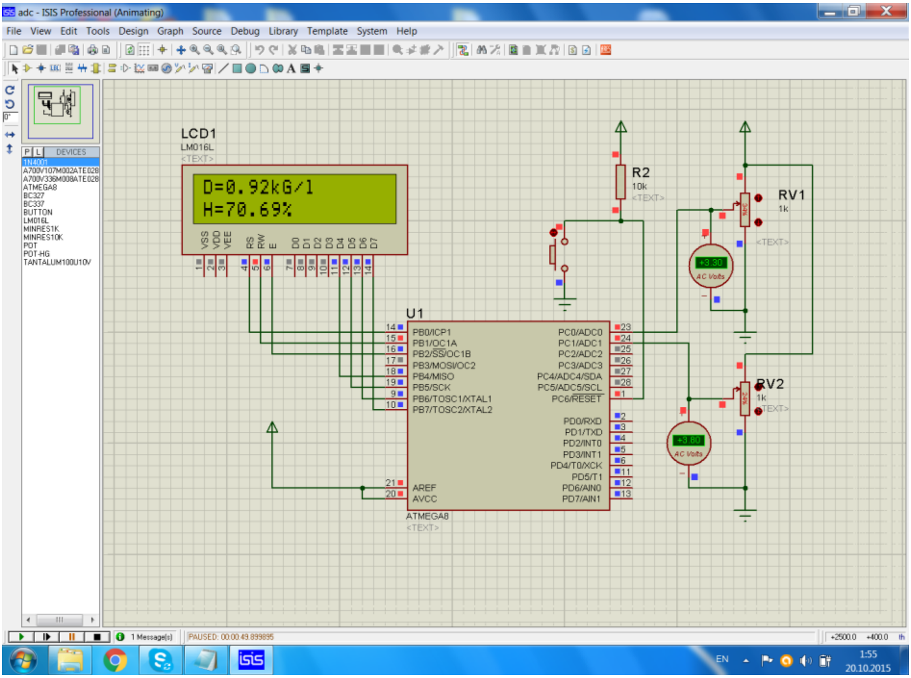

Figure 9. Schematic diagram of the device for measuring the level and density of the liquid

[4] Orkhan Afandiyev, Shain Alakbarov, Aynura Allahverdiyeva Measurement of the Levels and the Density of Liquids in Ship Reservoirs by Magnetic Levitation and Buoy Measuring Device // INDIA: International Journal of Science and Research (IJSR), Volume 7, Issue 8, August 2018, pp.44-49

In order for the schematic to function, a program for the microcontroller was developed, and tested using “Code Vision AVR”.

To calculate the error of the developed level and density sensor, the total of the known errors of its individual transducers was determined, including the main errors at its nodes, errors due to changes in ambient temperature, supply voltage variations, etc. In this case, all components are considered as random variables. Therefore, the distribution law for each component was determined, and its root mean square (RMS) value was calculated.

A performance report was conducted on the laboratory prototype of the buoy-type level sensor developed based on the principle of magnetic levitation for liquid level measurement. Based on the measurement results obtained during the experiments, the measurement range and the relative fundamental error of the transmitter unit of the developed laboratory prototype were determined.

The design drawings of the device for measuring liquid level based on the principle of magnetic levitation have been prepared.Figure 9 shows the appearance of the device developed, for measuring liquid level using the magnetic levitation principle.

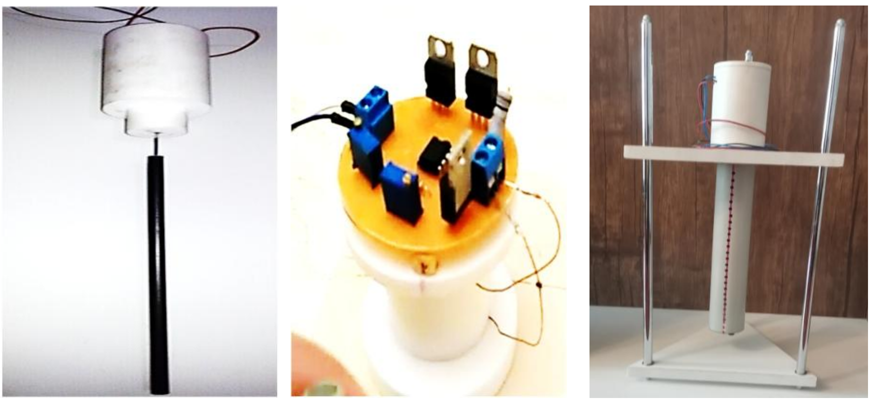

Figure 10. The appearance of the device developed for measuring liquid level using the MLS.

The presented device pertains to measurement technology, and can be used for high-precision measurement of liquid level, and density in ship steam boilers, oil tankers, and other similar open or closed environments [16][5].

The measuring range of the level measuring device is unlimited, and measurements can be carried out in liquids of any density. The device replaces the inductive transmitter with a galvanomagnetic transmitter. The device for level measurement consists, of several simple structural parts. Their manufacturing does not require complex technology or expensive materials, and allows for mass production.

As a result, it can be stated that the presented device has the following advantages: high measurement accuracy, absence of inertia, no temperature error, and output of information in the form of an electrical signal, and wide measurement range, and independence from the liquid density in level measurement, absence of mechanical contacts, and no use of a mechanical spring. A magnetic levitation system designed wide measurement range based on a new operating principle is capabie of continuously measuring the liquid level in various reservoirs.

As one of the modern efficient technologies, the innovative level measurement device-the magnetically suspended float-type level sensor-will enable more effective achievement of the set objectives.

[5] Afandiyev O.Z., Allahverdiyeva A.T. Patent Application Materials for the "Float-Type Level Meter" Device, Center for Expertise of Industrial Property Objects (AzPATENT) LLC, Official Bulletin, No.12, Baku - 2016, p.9.

SUMMARY OF RESULTS

1. Based on the research, the application features of magnetic levitation in measuring technological processes on ships were investigated, and the following results were obtained:

2. An analysis of the existing schemes for the implementation of magnetic levitation was carried out, and a summary of the issues solved with its help-aimed at increasing accuracy, sensitivity, and operational reliability of measurement systems-was presented. Using elements of integrated microelectronics, the selection of the galvanomagnetic - type magnetic levitation system (SML) as the best choice variant was substantiated.

3. The main issues of research aimed at increasing the operational efficiency of high-precision and high-sensitivity control and measurement systems based on the magnetic levitation principle were summarized. It was shown that, depending on the type of the controlled parameter, and the field of operation, the the best choice variant of the MLS should be selected.

4. The theoretical basis for the construction of a galvanomagnetic-type MLS with temperature compensation of the inductance of the levitating magnetic core was developed. A functional prototype of this type of MLS was built, enabling real-time monitoring of changes in the parameters of individual elements, and blocks.

5. A new mathematical model of the MLS was proposed in the form of a transfer function related to the automatic regulation of the solenoid current. This makes it possible to ensure the stability of the levitating magnetic core under the required, and sufficient conditions, depending on the time constant of the corrective element.

6. The main parameters of the individual nodes of the electronic circuit for controlling the magnetic levitation process were calculated. Based on the modeling of the transient processes in the studied system, the dynamic performance indicators of the MLS were evaluated, forming the foundation, for the design of modern control, and measurement systems.

7. A functional and structural diagram of a more efficient

buoyancy-based density, and level measuring device - capable of highly sensitive and precise measurements based on the magnetic levitation principle - was developed. During the work process, the dynamic equilibrium equations of the external forces acting on the level measurement device were derived, and due to the absence of friction under local weightlessness conditions, high accuracy was achieved over a wide measurement range.

8. By confirming the force characteristics of the level meter, the optimal values of its design parameters were determined. Based on the mathematical model of the device, its dynamic properties were investigated, and the stability conditions of the magnetic core were identified. The transient process of the magnetic levitation system of the level measurement device has been established.

9. A block diagram ensuring the operational algorithm of the level measurement device was developed, a functional prototype was prepared based on the circuit diagram, and an analysis of the errors of the float-type level sensor was provided.

The main content of the dissertation has been published in the following scientific works:

1. Afandiyev O.Z., Azizov R.R., Allahverdiyeva A.T. Influence of Constructive Parameters on the Force Characteristics of Magnetic Suspensions // Baku: Scientific Works of Azerbaijan State Marine Academy – 2014., No.1, pp. 117-121.
2. A.T. Allahverdiyeva Application of Magnetic Levitation System in Measurement Technology // Baku: 9th International Scientific-Technical Conference Dedicated to the 91st Anniversary of the National Leader Heydar Aliyev, Scientific Works of Azerbaijan State Marine Academy – 2014., No.2, pp. 85-90.
3. Afandiyev O.Z., Allahverdiyeva A.T. Some Theoretical Aspects of Levitation of Soft Magnetic Core in Electromagnetic Systems // Baku: Scientific Works of Azerbaijan State Marine Academy - 2015, No.2, pp. 156-158.
4. Afandiyev O.Z., Alekperov Sh.Sh., Allahverdiyeva A.T. Measurement of Level and Density of Liquids Using Magnetic Levitation and Float Type

Level Meter // Baku: Scientific Works of National Aviation Academy – 2016., No.18, pp. 25-31.
5. A.T. Allahverdiyeva Comparative Analysis of Magnetic Levitation Schemes and Selection of a Typical Rational Scheme // Baku: International Scientific-Technical Conference at Azerbaijan Technical University – 2016., pp. 55-58.
6. A.T. Allahverdiyeva Measurement of Liquid Level and Density Using Magnetic Levitation Float-Type Level Meter // Baku: XX Republican Scientific Conference of Doctoral Students and Young Researchers, Azerbaijan State University of Oil and Industry - 2016., pp. 290-292.
7. Efendiyev O.Z., Allahverdiyeva A.T. Research on Dynamic Properties of Magnetic Levitation Systems, and Determination of Conditions Ensuring Stable Levitation of Magnetic Core // Baku: Energy Problems – 2016., No.4., pp. 25-31.
8. Afandiyev O.Z., Allahverdiyeva A.T. Patent Application Materials for the "Float-Type Level Meter" Device, Center for Expertise of Industrial Property Objects (AzPATENT) LLC, Official Bulletin, No.12, Baku – 2016., p.9.
9. Afandiyev O.Z., Azizov R.R., Allahverdiyeva A.T. Study of Dynamic Properties of Magnetic Levitation Systems // Novorossiysk: Admiral F.F. Ushakov State Maritime University, “Operation of Marine Transport”Collection No.1 (82), 2017., pp. 37-41.
10. Afandiyev O.Z., Allahverdiyeva A.T. Patent for “Float-Type Level Meter”, Baku - 2017.
11. Afandiyev O.Z., Allahverdiyeva A.T. Magnetic Levitation Float-Type Measuring Device for Determining Liquid Level and Density // Baku: International Scientific-Technical Conference, Azerbaijan State Marine Academy, 2018., pp. 149-152.
12. Orkhan Afandiyev, Shain Alakbarov, Aynura Allahverdiyeva Measurement of the Levels and the Density of Liquids in Ship Reservoirs by Magnetic Levitation and Buoy Measuring Device // INDIA: International Journal of Science and Research (IJSR), Volume 7, Issue 8, August 2018., pp.44-49.

13. Afandiyev O.Z., Alekperov Sh.Sh., Allahverdiyeva A.T. Investigation of the Possibility of Measuring Liquid Level and Density Using Magnetic Levitation Level Meter // Kyiv: Collection of Scientific Works "Navinti Technologies", Indexed in International Scientometric Bases, Issue 1(8), 2019., pp.81-87.
14. Afandiyev O.Z., Allahverdiyeva A.T., Shikiyev A.S. Method for Calculating Magnetic Induction of Cylindrical Cores from Hard Magnetic Materials // INDIA: International Journal of Current Research, Volume 11, Issue 03, March 2019., pp. 2388-2391.
15. Allahverdiyeva A.T. Determination of Electromagnetic Pulling Force of Solenoid with Solid Magnetic Core // Baku: Journal of the Azerbaijan Engineering Academy, Volume 11, No.4., 2019., pp. 52-57.
16. Allahverdiyeva A.T., Shikiyev A.S. Study of a Vibration Measuring Device Operating on the Principle of Magnetic Levitation // 15th. International Scientific-Technical Conference Dedicated to the 97th. Anniversary of National Leader Heydar Aliyev, Azerbaijan State Marine Academy, 2020., pp. 66-69.
17. Afandiyev O.Z., Allahverdiyeva A.T. Selection of a Method for Increasing the Stability Margin of Magnetic Levitation Systems // Novorossiysk: Admiral F.F. Ushakov State Maritime University, International Scientific-Practical Conference, 2020., pp. 175-177.
18. Allahverdiyeva A.T. Determination of Magnetic Levitation System Parameters // Kaluga: 2020., pp. 3-5.
19. A.T. Allahverdiyeva Measurement of Liquid Properties Using Magnetic Levitation Float-Type Level Meter in Ship Tanks // Denmark: V International Scientific and Practical Conference "Global and Regional Aspects of Sustainable Development", October 2021., Copenhagen, № .82, pp.194-203.
20. Orkhan Afandiyev, Aynura Allahverdiyeva Determining the Influence of Ambient Temperature on Magnetic Induction of Levitating Magnetic Core // Baku: Azerbaijan State Marine Academy, International Scientific-Technical Conference on "Innovative Development Prospects of Technical and Natural Sciences" - 2021, pp.81-85.

21. Piriyeva N.M., Allahverdiyeva A.T. Characteristics of Magnetic Circuit of Induction Levitation System // Bulletin of Science, №.7(5), pp.309-318, ISSN 2712-8849 - 2023.
22. Nijat Mammadov, Aynura Allahverdiyeva, İlkin Marufov Study of application characterstics of cylindrical structure induction levitator in general and vertical axis wind turbines // Journal Przeglad Elektrotechniczny ISSN 0033-2097-2023.,№10., pp.196-199.
23. Afandiyev O.Z, Allahverdıyeva A.T. Determination of the environmental temperature degree on magnetic levitation core induction // Azerbaijan State Marine Academy, - Baku: RISK-2023. Conference International journal 18 № 5 (75), pp. 304-307.
24. O.Z. Afandiyev, A.T. Allahverdıyeva, S.N. Aliyeva, Y.F. Afandiyeva Automatic duist measuriment system using a magnetic suspension // International Journal on "Technical and Physical Problems of Engineering" (IJTPE) ISSN 2077-3528-2023, İssue 57, volume 15, №4., pp. 1-5.

Personal Contribution in Co-Authored Publications:

Aynura Tavakkul Allahverdiyeva, a doctoral student at the "Ship Electro automatics" Department of the Azerbaijan State Maritime Academy (ASMA), has independently completed works numbered [2, 5, 6, 15, 18, 19];

In the works numbered [1, 3, 4, 7, 8, 9, 10, 11, 12, 13, 14, 16, 17, 20, 21, 22, 23, 24], the formulation of research problems, theoretical investigations, processing of results, development of proposals, and formation of scientific theses were carried out by the doctoral student Aynura Tavakkul Allahverdiyeva. The remaining parts were completed the equally by the co-authors;

The works numbered [3, 7, 8, 11, 17, 20, 23] were written upon the recommendation of the scientific supervisor as a result of joint discussions among the authors, with the aim of mastering the theoretical aspects of the problem.

The defense of the dissertation will take place on Octember 10, 2025, at 14:00., during the meeting of the One-Time Dissertation Council registered under number BFD 2.02/2 at the Supreme Attestation Commission under the President of the Republic of Azerbaijan, based on the ED 2.02 Dissertation Council operating, under the Azerbaijan State Oil and Industry University (ASOIU) PLE.

Address: AZ 1010, Baku city, 34 Azadliq Avenue.

The dissertation can be found in the library of “Azerbaijan State Oil and Industry University” PLE.

The electronic version of the dissertation, and abstract is posted on the official website, of the Azerbaijan State Oil and Industry University (ASOIU) PLE.

The author’s abstract was sent to the required addresses on
08 september 2025.

Signet for print: 30.07.2025
Paper format: A5
Volume: 44 477
Nomber of hard copies: 30