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SENSOR TECHNOLOGY FOR FLOATING DOCK BALLAST SYSTEM WITH TECHNICAL DIAGNOSTICS

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INTRODUCTION

The rapid development of computer technology contributes to its wide application in many branches of the national economy, including shipbuilding. Large-capacity floating docks equipped with specialized computer systems (SCS) are used more and more frequently (compared to dry docks) for the maintenance and repair of large-sized vessels. At the same time, floating docks, despite their structural complexity and high operating cost, are rapidly becoming the main means of lifting vessels of various purposes and tonnage for carrying out various types of repairs.

The modern level of automation of floating docks with the presence of constant operator control of their parameters is the reason for the increased time duration of the processes of raising or lowering the vessel, insufficient economic efficiency of using the floating dock.

Increasing the productivity and reliability of dock operations is possible due to the creation of new and modification of existing SCS of parametric control and controlled stabilization of floating docks with a hierarchical structure and computer components synthesized based on modern methods and means of research of embedded real-time systems, control and diagnostic support, intelligent identification methods, cloud computing technologies, etc. Hierarchical SCS of parametric control and controlled stabilization of floating docks with distributed software and hardware components, in which decentralized information processing is carried out at each of the hierarchical levels, have a special perspective.

Operational control of ballast compartments' parameters with high precision and timely control of ballast supply for dock operations performing as well as ensuring of the absence of dangerous list and large deflection is a complex problem.

Consequently, the problem of efficient operation of complex technical objects, which includes a floating dock, arises in the field of precise and reliable measurement. So, solutions to tasks of sensors' choice and their technical diagnostics should be obtained along with automation of floating dock. The questions of parameters measuring and calculating of the floating dock in one way or another are considered in a number of scientific papers[17]. Therefore, the systems of measurement and control of floating docks' parameters are developed using sensors, which are based on different principles of action. In particular, the sensors, that are based on pulsed reflection method and have a single electronic and structural design are used for determination of liquid level parameters of the floating dock[18]. The disadvantage of such solution is the significant mass-size indicators and specialized pipes that have the ability to property to contaminate. In addition, radar-type sensors find an application for liquid level measurement in ballast compartments. Some sensors allow measuring the level with high accuracy (up to 1 mm). In addition, the accuracy and stability of measurements do not depend on the effect of destabilizing factors (temperature of the medium, evaporation and dust in the tank, the aggressive nature of the controlled product, etc.) when using radar sensors. However, this method has a high cost service of automation level control systems due to the periodic carrying out of preventive checks of the radar sensors normalcy. In addition, membrane type sensors [19], in which the deflection of membranes under the pressure of a water column is converted into the resistance of the electrical circuit, are used. Such sensors have flaws related to the sensitivity to frost, which may cause a failure to conduct an accurate measurement.

The use of new types of sensors and modern principles of construction of distributed SCS control will allow solving a number of problems and creating a universal highly efficient computer system for monitoring the working parameters of the floating dock with available technical diagnostics of the sensors.

1. Problems of operations of submersion and surfacing of a floating dock and features of the ballast system

A floating dock is a complex engineering structure, which is mainly designed to perform dock operations of submersion and surfacing. The floating dock is used for lifting the vessel out of the water, launching the

[17] Yang, G., Liang, H., Wu, C. Deflection and Inclination Measuring System for Floating Dock Based on Wireless Networks. International Journal Ocean Engineering. 2013, Vol. 69, P. 1-8.

[18] Zhukov, Yu., Gordeev, B., Zivenko, A., Nakonechniy A. Polymetric Sensing in Intelligent Systems. Chapter in the book Advances in Intelligent Robotics and Collaborative Automation. River Publishers. 2015, Vol. 10, 211-232.

[19] Topalov, A., Kozlov, O., Kondratenko Y. Control Processes of Floating Docks Based on SCADA Systems with Wireless Data Transmission. Perspective Technologies and Methods in MEMS Design: Proceedings of the International Conference MEMSTECH-2016. Lviv-Poljana, Ukraine. April 20 – 24, 2016, P. 57-61.

vessel, and in some cases as a floating platform for transporting the vessel along shallow waterways[20]. General view of a floating dock with a vessel installed on the slipway deck is shown in fig. 1. In addition, with the help of a floating dock, preventive inspection and repair of the underwater part of the vessels hull and external elements of the propeller-rudder complex are carried out[21].

Fig. 1. General view of a floating dock with a vessel

In the history of the use of floating docks, there are serious accidents and emergencies: flooding of the dock, fracture of the towers, corrugations on the towers, etc., for example, in 2018, at the 82nd shipyard in the village of Roslevo, Murmansk region (Russian Federation), during the reconstruction of the aircraft carrier «Admiral Kuznetsov», the floating dock PD-50 was sunk. Another case occurred near San Francisco, USA in

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[20] Kwon J.W., Seo J. Docking Control on Both Stationary and Moving Stations Based on Docking Formation. Electronics Letters. 2014, V. 50, №6. P. 436–438.

[21] Apostolidis A., Kokarakis J., Merikas A. Modeling the Dry-Docking Cost: The Case of Tankers. Journal of Ship Production and Design. 2012, № 28. P. 134–143.

2016, a 160-meter floating dock sank during the crossing by the tugboat Ocean ranger. There is also a well-known case in the village of Slovianka, Primorsky Krai, Russian Federation in 2018, when the floating dock PD-169 broke into pieces and sank during docking operations.

Some types of accidents are shown in fig. 2, and the general view of the broken floating dock with the vessel in fig. 3.

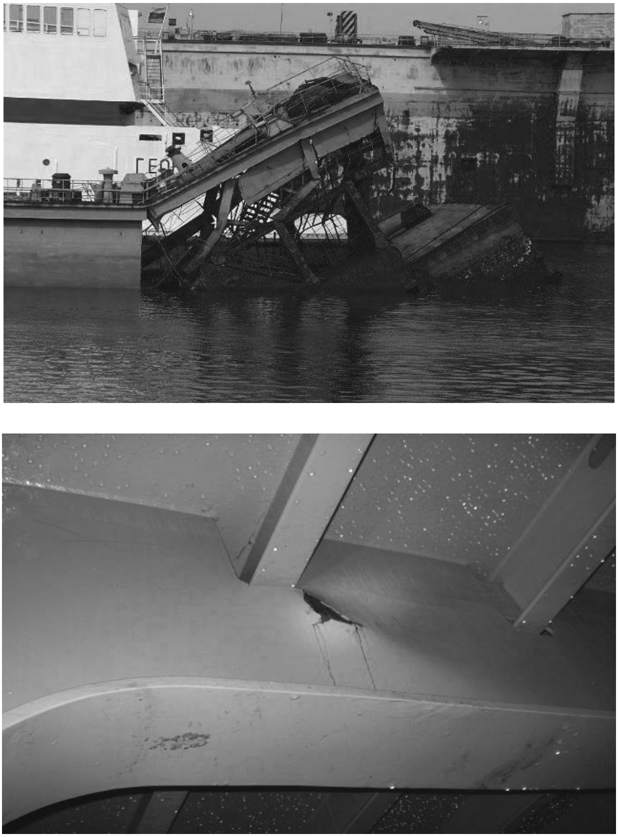

Fig. 2. Deformations of the floating dock body: a) significant bending of the tower and pontoon; b) metal deformation under the slipway-deck

Fig. 3. General view of a broken floating dock with a vessel

The lifting of the vessel by the floating dock is carried out in the following sequence: the dock, receiving water through the clinches into the ballast compartments of the pontoon and towers, sinks to a depth sufficient for the installation of the vessel, then the vessel is started over the support devices of the slipway-deck and from the ballast water is pumped out of the compartments with pumps and the vessel is landed on the dock supports; the process of raising the vessel ends with the final floating of the dock. The vessel is launched into the water using the operation of submerging the floating dock and taking the vessel out of the slipway-deck.

For the efficient functioning and carrying out of docking operations, the floating dock uses the following systems: ballast, vacuum, cleaning, pneumercator, etc., which ensure the operation of executive mechanisms and the dock as a whole[22].

The ballast system of the floating dock is mainly intended for filling the ballast compartments with water during submersion and for pumping water out of them when the floating dock surfaces. The main elements of the ballast system are specialized pumps, pipelines (receiving, outflowing and diluting), various shut-off valves.

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[22] Lovyagin M.A., Korsakov V.M., Kaganer Y.B. Metal floating docks. L.: Shipbuilding. 1964, 336 p. (in Russian)

In practice, two ballast system schemes are used[23]: linear and ring. With the linear scheme (fig. 4), each ballast pump is located on one side of the pontoon of the floating dock and is connected to a distribution box that distributes the processes with the corresponding latches to the ballast compartments. The distribution boxes themselves are connected to each other by linear pipelines with latches.

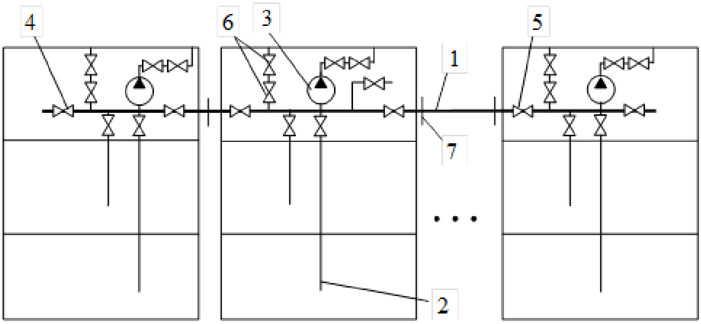


Fig. 4. Linear diagram of the ballast system: 1 – highway; 2 – cutting process; 3 – pump; 4 – cutting latch; 5 – cut-off latch on the main line; 6 – double shutters on external openings; 7 – disconnecting flanges between pontoons

On modern docks of large sizes, a ring scheme (fig. 5) of the ballast pipeline is usually used. The ring circuit consists of two on-board trunks connected by at least two jumpers. The main line connects ballast pumps and ballast compartments with valves. Such a system allows, in the event of failure of a part of the pumps in the ring system, to pump water from any compartment with other pumps.

[23] Rashkovsky A.S., Slutsky N.G., Konnov V.N., Shchedrolosev A.V., Uzlov L.N. Designing, technology and organization of composite floating docks construction. Nikolaev: RAL-polygraphy. 2008, 614 p. (in Russian)

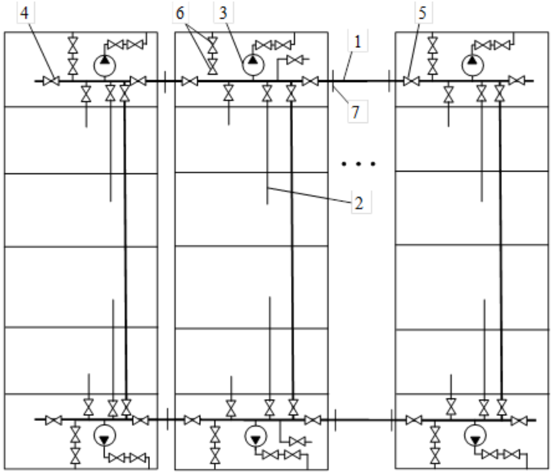


Fig. 5. Ring diagram of the ballast system: 1 – highway; 2 – cutting process; 3 – pump; 4 – cutting latch; 5 – cut-off latch on the main line; 6 – double locks on external openings; 7 – disconnecting flanges between pontoons

The main operational requirement for ballast systems of various types is the provision of water pumping by all available ballast pumps or part of them in case of failure of one or more pumps. The ability to simply and quickly turn on or turn off individual pumps and, as a consequence, the ability to pump water from any compartment of the dock at the same time allows the dock to submersion or surfacing with minimal deflection, which ensures safe docking or removal of the vessel from the dock. The diameters of the pipelines of the system should ensure that the dock and the vessel can surfacing in 50-80 minutes.

Regardless of the pipeline scheme, the ballast system of the floating dock is served by several pumps. Centrifugal and propeller pumps are distinguished among the types of pumps used. Productivity and the number of pumps are chosen based on the considerations of the given ballast water pumping time and ensuring the speed of water movement in the ballast pipeline of 2-2.5 m/s. Also, it is desirable to choose pumps so that when the pressure drops, the productivity («consumption») increases at constant values of revolutions and power consumption. In these conditions, water is pumped out of the ballast compartments the fastest.

To determine the level (quantity) of ballast in the compartments of the floating dock, the following can be used: a pneumatic system consisting of copper pipes of small diameter (5...8 mm), sensors installed in ballast compartments, hydrometers located in the CPU, etc.

During the docking operation, it is necessary to systematically monitor the exit of air from the air pipes, to prevent sudden changes in the deflection of the dock, to check the inflow of water into the ballast compartments using hydrometers.

2. Schematic location of the sensors measuring the operating parameters of the floating dock

While the floating dock is performing submersion and surfacing operations, it is necessary to control the level, volume of liquid in the ballast complex, as well as the parameters of the landing and strength of the floating dock. Accordingly, the hull and ballast complex of the floating dock are equipped with sensors.

To control the landing parameters (draft, list, trim) and the hogging/sagging arrow, the hull of the floating dock is equipped with hydrostatic level sensors that simultaneously continuously record their electrical signals, while the sensors are installed along the sides, and the current values of the operating parameters are calculated based on the recorded electrical signals.

Schematic arrangement of SCS sensors for the floating dock hull is shown in fig. 6, where it is marked: FLS – fixed liquid level sensor; HOPS – on-board liquid level sensor; S_{13} – distance between $HOPS_{1,1}$ and $HOPS_{1,2}$; S_{35} – distance between $HOPS_{1,2}$ and $HOPS_{1,3}$; S_{15} – distance between $HOPS_{1,1}$ and $HOPS_{1,3}$; S_{12} – $HOPS_{1,1}$ and $HOPS_{2,1}$; and $S_{12} = S_{34} = S_{56}$; $S_{13} = S_{35} = S_{24} = S_{46}$; $S_{15} = S_{26}$.

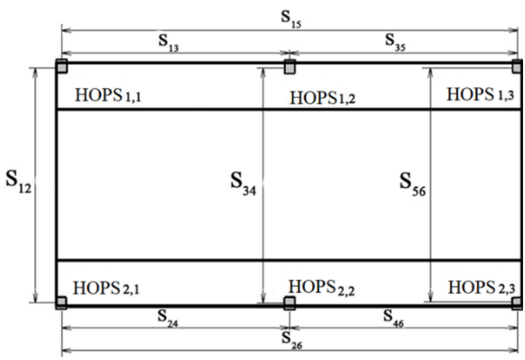


Fig. 6. Schematic arrangement of sensors SCS on the hull of the floating dock (top view)

Hydrostatic sensors $HOPS_{1,1}$, $HOPS_{1,2}$, $HOPS_{1,3}$, $HOPS_{2,1}$, $HOPS_{2,2}$, $HOPS_{2,3}$ shall be installed evenly three sensors along the port and starboard sides outside the floating dock, as close as possible to its bottom, with $HOPS_{1,1}$ and $HOPS_{1,3}$ are installed at the extreme points of the starboard side, $HOPS_{2,1}$ and $HOPS_{2,3}$ – at the extreme points of the port side, $HOPS_{1,2}$ – midway between $HOPS_{1,1}$ and $HOPS_{1,3}$ sensors on the starboard side, and $HOPS_{2,2}$ – midway between $HOPS_{2,1}$ and $HOPS_{2,3}$ sensors on the port side, the current values of draught, list, trim and hogging/sagging arrow of the floating dock are calculated based on the recorded electrical signals of the hydrostatic sensors using the hydrostatic method and geometric dependencies between the position of the sensors and the water surface.

To accurately control the level and volume of liquid in the ballast complex, each ballast tank is equipped with certain sensor equipment. Regardless of the ballast system, the general view of the location of ballast compartments on a number of floating docks is shown in the fig 7. From the drawings, one can see that the ballast tanks of large capacity BT13-BT18 are located in the central part of the dock, and ballast tanks of small capacity BT1-BT12 – in the bow and stern.

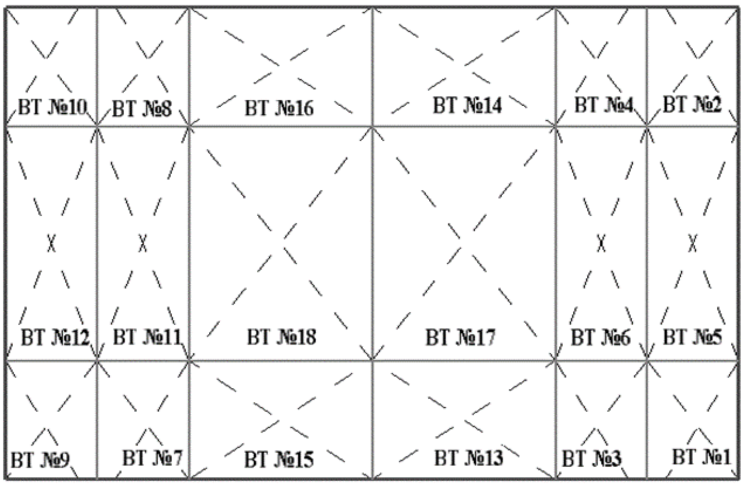


Fig. 7. The layout of the ballast tanks

Let us consider in more detail a single ballast tank (BT) of the floating dock (fig. 8). A ballast tank is equipped with the following devices: a hydrostatic level sensor (HLS) combined with a temperature sensor (TS), located in the center of the bottom of the ballast tank, an overpressure sensor (PS), a discrete fixed level sensor (FLS), a flow meter (FM).

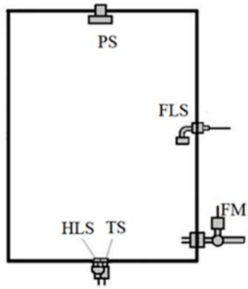


Fig. 8. Schematic arrangement of SCS sensors in the ballast tank

Sensor components (HLS, FLS, TS, FM, PS) are used in the ballast complex to obtain information on the current level value, fixed level value, as well as liquid ballast temperature, liquid flow rate and overpressure in the ballast tanks.

In order to implement the technical diagnostics in the shown BT (fig. 8), the FLS is mounted on the side wall of the ballast tank and is located above the HLS at a certain fixed height. An approach is used in which the condition of the HLS is checked at discrete intervals by comparing the current liquid level with the diagnostic level.

The hydrostatic method of level measurement is used to obtain the level of homogeneous liquids in tanks without significant fluctuations in the working environment. This method allows measuring the level in a wide range with a sufficiently high accuracy (up to 0.1%) at high extent of overpressure and temperature of the working medium.

Calculation of the level and volume of ballast tank liquid. To determine the current level and volume of liquid in the ballast tank, the hydrostatic method of measuring the level of liquid ballast is used.

According to the hydrostatic method of measurement, at zero heel and list angles of the floating dock, the real value of the liquid level h in each ballast tank is determined by the formula[24]:

$$h = \frac{P_{\text{L}}}{\rho_{\text{L}} g}, \qquad (1)$$

[24] Zhdankin V. Instruments for measuring the level. Modern automation technologies. № 3. 2002, P. 6-19. (in Russian)

where P_L is the value of the hydrostatic pressure of the fluid measured by the HLS; ρ_L is the density of the working fluid; g is the acceleration of free fall.

The value of liquid density ρ_L depends on various factors such as temperature, pressure, composition, physical and chemical characteristics. Most of all, the value of the liquid density ρ_L is influenced by the value of the liquid temperature t_L, °C, and therefore the sensor *TS* plays an important role in determining the current value of the liquid density ρ_L (according to the relevant reference tables)[25].

The presence of a certain non-zero value of the list angle θ or trim ψ affects the accuracy of liquid level measurement in tanks.

The value of the liquid level *h*, measured with the help of the HLS at a certain value of the trim angle ψ, is slightly different from the value obtained at a zero value of the trim angle ψ. In this case, the real value of the liquid level in the tank is determined by the formula

$$h = \frac{h_\psi}{\cos\psi} = \frac{P_\psi}{\rho_L g \cdot \cos\psi}, \tag{2}$$

where h_ψ is the height of the hydrostatic column of water to the inclined surface at the trim angle ψ; $P\psi$ is the value of the hydrostatic pressure of the liquid measured by the HLS at the trim angle ψ.

Accordingly, the calculation of the liquid level in each of the ballast tanks at the list θ of the floating dock is determined by the formula

$$h = \frac{h_\theta}{\cos\theta} = \frac{P_\theta}{\rho_L g \cdot \cos\theta}, \tag{3}$$

where h_θ is the height of the hydrostatic column of water to the inclined surface at the list angle θ; P_θ is the value of the hydrostatic pressure of the liquid measured by the HLS at the list angle θ.

The level of liquid in the ballast tank with simultaneous consideration of the list and trim (1, 2 degrees) of the floating dock is calculated by formula (4) for the HLS.

$$h = \frac{P_{\theta\psi}}{\rho_L g} \cdot \frac{1}{\cos\theta \cdot \cos\psi}, \tag{4}$$

where $P_{\theta\psi}$ is the value of the hydrostatic pressure of the liquid measured with the help of the HLS at the list angle θ and trim ψ of the floating dock.

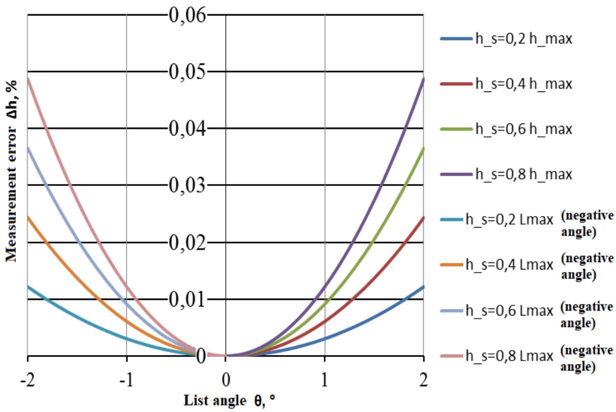
The volume of liquid in the tanks is calculated based on the polynomial formula

[25] Topalov A., Kozlov O., Kondratenko Y. Control Processes of Floating Docks Based on SCADA Systems with Wireless Data Transmission. Perspective Technologies and Methods in MEMS Design. Proceedings of the International Conference. Lviv-Poljana, Ukraine. 2016, P. 57–61.

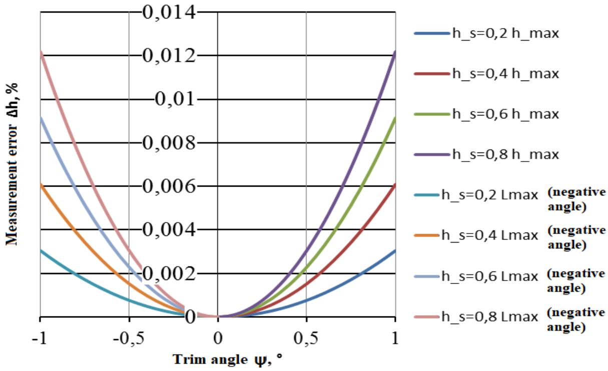
$$V_r = a_4 h^4 + a_3 h^3 + a_2 h^2 + a_1 h + a_0, \qquad (5)$$

where a_0, a_1, a_2, a_3, a_4 are experimentally obtained polynomial coefficients.

This approach (5) makes it possible to unify the calculations of the liquid volume for tanks of regular shapes (box, cylinder) and complex geometric shapes, which are very common in marine technology. The values of the coefficients of the fourth degree polynomial are calculated using specialized software that approximates the provided table of tank filling volumes (set for each tank) with the implementation of the least squares method.



a)



b)

Fig. 9. Values of errors of liquid level measurement in ballast tank at: a) floating dock list up to 2º; b) floating dock trim up to 1º

The error of measurement of the liquid level in the ballast tank at a certain trim ψ of the floating dock is determined by the following expression[26]

$$\Delta h = \frac{h - h_s}{h_{max}} = \frac{h_s}{h_{max}\cos\psi} - \frac{h_s}{h_{max}}, \quad (6)$$

where h_{max} is the maximum value of the tank filling height; h_s is the tank filling value from the maximum value.

Accordingly, the measurement of the liquid level in the ballast tank at a certain list θ of the floating dock is determined by the following expression

$$\Delta h = \frac{h_s}{h_{max}\cos\theta} - \frac{h_s}{h_{max}}. \quad (7)$$

Thus, the results of errors in measuring the liquid level at different angles of list and trim are shown in fig. 9.

To measure the hogging/sagging arrow, draft T_o, list angles θ and trim ψ of the floating dock, hydrostatic pressure sensors are used, which are located evenly in three sensor spots along the port and starboard sides outside the floating dock as close to its bottom as possible.

Calculation of the floating dock draft. Fig. 10 shows a floating dock without list and trim. The draught of the floating dock T is determined based on the readings of the sensors $HOPS_1$ – $HOPS_6$, according to the dependence

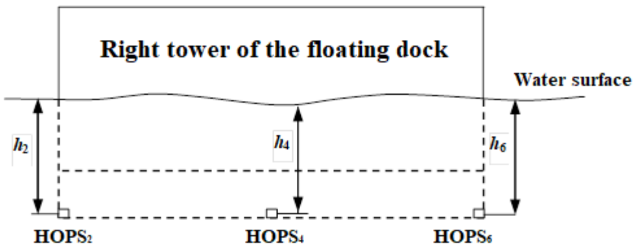


Fig. 10. Scheme of a floating dock immersed in water at a certain draft: starboard view

[26] Kondratenko Y.P., Kozlov O.V., Korobko O.V., Topalov A.M. Improvement of the computerized information-measuring system for controlling the level and volume of liquid in ship tanks. International Conference on Automatic Control and Information Technologies ISACIT-2015. Materials of the 3rd International Conference on Automatic Control and Information Technologies. Kyiv. 2015, P. 112-115. (in Ukrainian)

$$T_o = \frac{h_1 + h_2 + h_3 + h_4 + h_5 + h_6}{6} = \frac{P_1 + P_2 + P_3 + P_4 + P_5 + P_6}{6\rho_L g}, \qquad (8)$$

where $P_1 - P_6$ are the values of hydrostatic pressure of the water column measured with the help of sensors $HOPS_1 - HOPS_6$; $h_1 - h_6$ are the values of water level measured with the help of sensors $HOPS_1 - HOPS_6$, respectively.

Calculation of the floating dock list. The geometric model of the floating dock with the list on the right tower is shown in fig. 11.

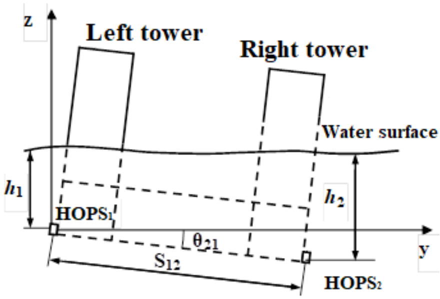


Fig. 11. Diagram of a floating dock with list θ_{21} on the right tower

The following formula is used to determine the sine of the list angle θ_{21} of the right tower of the floating dock

$$\sin\theta_{21} = \frac{\Delta h_{21}}{S_{12}} = \frac{h_2 - h_1}{S_{12}} = \frac{\left(\frac{P_2}{\rho_L g}\right) - \left(\frac{P_1}{\rho_L g}\right)}{S_{12}} = \frac{P_2 - P_1}{\rho_L g S_{12}}, \qquad (9)$$

where Δh_{21} is the difference of water level values measured with the help of the sensors $HOPS_1$ and $HOPS_2$, respectively, $\Delta L_{21} = L_2 - L_1$; θ_{21} is the list angle of the floating dock, which is determined by the difference of readings of the sensors $HOPS_1$ and $HOPS_2$; S_{12} is the distance between the sensors $HOPS_1$ and $HOPS_2$.

Thus, the list angle θ_{21} of the floating dock can be calculated using the difference of the readings of the sensors $HOPS_1$ and $HOPS_2$:

$$\theta_{21} = \arcsin\left(\frac{\Delta h_{21}}{S_{12}}\right) = \arcsin\left(\frac{h_2 - h_1}{S_{12}}\right) = \arcsin\left(\frac{P_2 - P_1}{\rho_L g S_{12}}\right). \qquad (10)$$

Similarly, the list angles θ_{43} and θ_{65} for the floating dock are determined based on the readings of the sensors $HOPS_3$ and $HOPS_4$, $HOPS_5$ and $HOPS_6$. The average list angle is determined as an arithmetic mean based on the readings of hydrostatic pressure sensors $HOPS_1$-$HOPS_6$.

Calculation of the floating dock trim. The appearance of the geometric model of the floating dock with a bow trim is shown in fig. 12.

The following formula is used to determine the sine of the bow trim angle of the floating dock:

$$\sin\psi_{62} = \frac{\Delta h_{62}}{S_{26}} = \frac{h_6 - h_2}{S_{26}} = \frac{\left(\frac{P_6}{\rho_L g}\right) - \left(\frac{P_2}{\rho_L g}\right)}{S_{26}} = \frac{P_6 - P_2}{\rho_L g S_{26}}, \quad (11)$$

where Δh_{62} is the difference of water level values measured with the help of $HOPS_6$ and $HOPS_2$ sensors, respectively, $\Delta L_{62} = L_6 - L_2$; ψ_{62} is the angle of the floating dock trim, which is determined by the difference of readings of $HOPS_6$ and $HOPS_2$ sensors; S_{26} is the distance between $HOPS_2$ and $HOPS_6$ sensors.

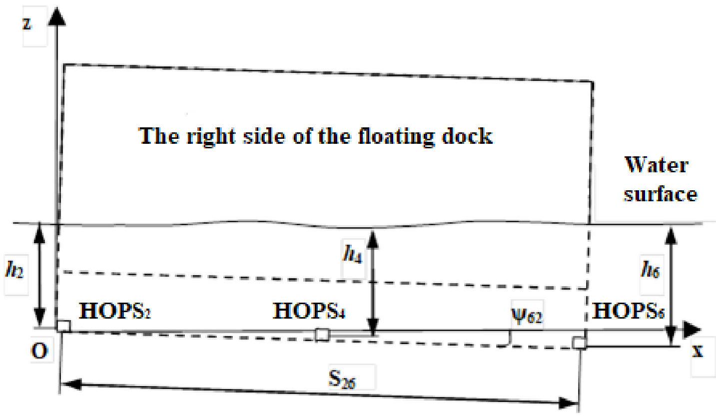


Fig. 12. Exterior of the floating dock with bow trim ψ_{62}

Thus, the trim angle of the floating dock can be calculated using the difference between the readings of the sensors $HOPS_6$ and $HOPS_2$:

$$\psi_{62} = \arcsin\left(\frac{\Delta h_{62}}{S_{26}}\right) = \arcsin\left(\frac{h_6 - h_2}{S_{26}}\right) = \arcsin\left(\frac{P_6 - P_2}{\rho_L g S_{26}}\right). \quad (12)$$

Similarly, the trim angle ψ_{51} for the floating dock is determined based on the readings of the sensors $HOPS_1$ and $HOPS_5$. The average trim angle of the floating dock is found as an arithmetic mean based on the readings of hydrostatic pressure sensors $HOPS_1$, $HOPS_2$, $HOPS_5$ and $HOPS_6$.

Calculation of hogging/sagging arrows of the floating dock. The appearance of the geometric model of the floating dock with bow trim and hull deflection is shown in fig. 13.

The deflection value H_{SB} deflection value of the right tower of the floating dock is determined as follows:

$$H_{SB} = h_4 - h_{4T}\,, \tag{13}$$

where h_{4T} is the theoretical value of the level before the floating dock deflection; h_4 is the real value of the level after the floating dock deflection.

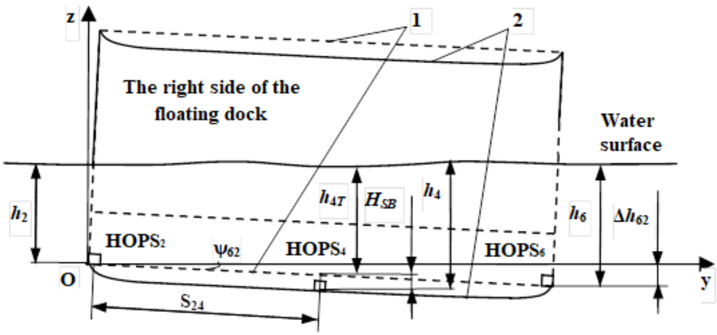


Fig. 13. Exterior view of the floating dock with bow trim and hull deflection: 1 – initial position; 2 – deflection

In turn, the theoretical value of the h_{4T} level is calculated by the formula

$$h_{4T} = h_2 + S_{24}\sin\psi_{62} = \frac{P_2}{\rho_L g} + S_{24}\sin\psi_{62}\,, \tag{14}$$

where S_{24} is the distance between the sensors HOPS $_2$ and HOPS $_4$. So,

$$H_{SB} = h_4 - \left(h_2 + S_{24}\sin\psi_{62}\right) = \frac{P_4}{\rho_L g} - \left(\frac{P_2}{\rho_L g} + S_{24}\sin\psi_{62}\right) \tag{15}$$

A positive value of the difference between the theoretical value of the h_{4T} level and the real value of h_4 measured with the help of the $HOPS_4$ sensor indicates the presence of deflection of the right tower of the H_{SB} floating dock. A negative value of this difference, in turn, indicates the presence of a bend of the right tower of the S_{SB} floating dock.

Thus, given $\begin{cases} h_4 - h_{4T} = H_{SB} \text{ at } h_4 - h_{4T} > 0 \\ h_4 - h_{4T} = S_{SB} \text{ at } h_4 - h_{4T} < 0 \end{cases}$ we obtain:

$$H_{SB}\,(\cup)\,S_{SB} = \frac{P_4}{\rho_L g} - \left(\frac{P_2}{\rho_L g} + \mathrm{S}_{24}\sin\psi_{62}\right). \tag{16}$$

Similarly, the value of the deflection/bending arrow of the left tower of the floating dock is determined. The value of the deflection/bending $H\,(\cup)\,S$ arrow of the floating dock hull is found in accordance with the following dependence:

$$H\,(\cup)\,S = \frac{H_{LB}\,(\cup)\,S_{LB} + H_{SB}\,(\cup)\,S_{SB}}{2} =$$

$$= \frac{\left[\frac{P_3}{\rho_P g} - \left(\frac{P_1}{\rho_P g} + \mathrm{S}_{13}\sin\psi_{51}\right)\right] + \left[\frac{P_4}{\rho_P g} - \left(\frac{P_2}{\rho_P g} + \mathrm{S}_{24}\sin\psi_{62}\right)\right]}{2} \tag{17}$$

where S_{13} is the distance between the sensors $HOPS_1$ and $HOPS_3$.

This dependence (17) makes it possible to estimate the deflection when the center of gravity of the cargo (vessel or several vessels) is located in the middle slipway of the floating dock deck and the deflection when the center of gravity of the cargo (vessel or several vessels) is located in the fore and aft parts of the slipway of the floating dock deck.

3. Technical diagnostics of ballast level sensors of the floating dock complex

Technical diagnostics of floating dock sensors plays an important role during its operation. Especially the sensors of deflection/bending, liquid level, overpressure, etc. require diagnostics. One of the most important systems that requires diagnostics of sensors is the ballast system of the floating dock, which plays the most important role in the process of docking vessels.

Diagnostics consists in monitoring the state of HLS of each ballast tank in order to detect and prevent its failures. The technical condition of the HLS is characterized by factors that include the influence of climatic conditions, aging over time, adjustment operations of mechanical and electronic components, adjustments during maintenance or repair, replacement of faulty elements, etc.

Diagnostics is carried out with the help of diagnostic controls, which can be built-in and external. Built-in means allow continuous monitoring of the relevant parameters. With the help of external means periodic control is carried out[27]. To implement the proposed method of technical diagnostics, in each ballast tank, in addition to HLS and PS, which are located in the center of the bottom of the ballast tank, FLS is also used, which is located in the center of the connection at right angles to the side walls of the ballast tank. The FLS is installed above the HLS at a certain fixed height and an approach is used in which the state of the HLS is checked at discrete intervals by comparing the current liquid level h with the diagnostic level h_D.

In turn, the diagnostic level h_D of the liquid, which depends on the FLS signal, in the ballast tank, taking into account the slight list (1-2 degrees) of the floating dock, should be calculated by the following formula:

$$h_D = h_{FLS} - \operatorname{tg}\theta \cdot \frac{S_{BT}}{2}, \qquad (18)$$

where h_{FLS} is the distance (height) at which the FLS is installed, θ is the list angle, S_{BT} is the width of the ballast tank.

Thus, HLS, which is a pressure measuring device, and TS are used to obtain information about the current level h and water temperature in the ballast tank. In order to monitor the diagnostic value of the h_D level, a FLS in the form of a float sensor is required.

Since the diagnostic level h_D can be measured only in the absence of list θ and trim ψ, or in the presence of a slight list θ of the floating dock, the diagnostics of the HLS should be performed in the same conditions.

Let us consider the functional diagram of the system of automatic liquid level control in one of the ballast tanks with the diagnostics of the HLS (fig. 14). Diagnostics of HLS in other ballast tanks is performed in a similar way.

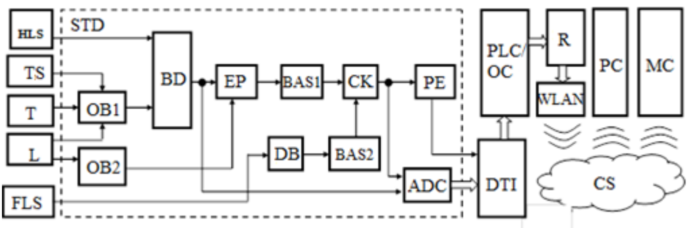


Fig. 14. Functional diagram of the computer system of automatic control of liquid level in the ballast tank with diagnostics of HLS

[27] Topalov A.M., Kondratenko Y.P., Kozlov O.V. A computerized system for remote diagnostics of level sensors of the floating dock ballast complex. Academic notes of TNU named after V.I. Vernadskyi. Series: technical sciences, informatics, computing and automation. 2018, No. 4, Part 2, Volume 29 (68). P. 19–25. (in Ukrainian)

The following notations are used in fig. 14: STD – system of technical diagnostics; HLS – liquid level sensor; L – listmeter; T – trimmetr; TS – temperature sensor; OB1 – computing unit used to determine the product of values corresponding to the list θ, trim ψ, liquid density ρ_L and gravitational acceleration g; OB2 – computing unit that determines the diagnostic liquid level h_D depending on the list angle θ; BD – division unit; EP – comparison element; BAS1, BAS2 – blocks of calculation of absolute value; FLS – fixed liquid level sensor; DB – differential block; CK – controlled key; PE – threshold element; ADC – analog-to-digital converter; DTI – data interface; PLC/OC – programmable logic controller or single chamber computer; R – router; WLAN – wireless communication modem; PC – personal computer; MC – mobile computer; CS – cloud service.

The essence of the proposed method for monitoring the liquid level in the ballast tank with technical diagnostics of the HLS is as follows. L and T measure the current values of list and trim of the floating dock, respectively. HLS measures the current value of the hydrostatic pressure of the liquid (Pa), and TS measures the current value of the liquid temperature (^oC). The liquid level h (m) is then determined using OB1 and BD. In turn, using OB2 and L, the diagnostic level h_D (m) is determined. Thanks to the EP block, the difference Δh between the diagnostic value of the level h_D and the value of the level h is calculated. The output of the BAS1 block determines the absolute value Δh_A of the obtained difference Δh, which corresponds to the measurement error of the DRR relative to the value of the diagnostic level h_D.

$$E = \begin{cases} 0, \text{ for } \Delta h_A > \Delta h_{\max} \\ 1, \text{ for } \Delta h_A \le \Delta h_{\max} \end{cases} \quad (19)$$

Thus, E = 0 indicates a malfunction of the HLS when the FLS is triggered, and the situation when E = 1 when the FLS is triggered corresponds to the serviceability of the HLS and its functioning with a given accuracy ($\Delta h_A \le \Delta h_{max}$).

The general diagnostic information is processed by the PLC or OC, the current value of h and Δh_A is recorded in the measurement database, which can then be used to determine the diagnostic parameters and correct the values of the liquid level in the ballast tank, and the measurement error signal E is transmitted via the Internet network to the cloud service, which is specially accessible from the PC and MC for operators.

Consider the approach of the proposed testing method using FPGA and VHDL model implemented in the form of an FSM diagram[28]. The proposed solution for the technical diagnostics of one ballast tank according to the VHDL model is shown in fig. 15.

Technical diagnostics according to the FSM scheme is carried out as follows:

– initialization of the first state S1, in which the values of faulty operation of the HLS sensor (ErHLS <= ‘0’) are cleared;

– in state S2, the measured signal from the HLS sensor (which is pre-digitized and corresponds to relative units of hydrostatic pressure) is calculated to obtain the value of the LPS liquid level in the ballast tank;

– in state S3 the difference DL is calculated between the fixed level value LF (FLS installation height) and the LPS level value obtained from the previous state;

– in state S4, the absolute value of L obtained by the difference DL is determined, which corresponds to the measurement error of the hydrostatic level sensor;

– in the state S5, the FSM diagram is branched for two scenarios. The first one is triggered under the condition (F4 = 1), which indicates the absence of FLS triggering (F1 = 0, F2 = 0), in which case the FSM diagram operation enters the cycle of states S1 → S2 → S3 → S4 → S5 → S1. The second scenario is possible if during the first scenario (cycle) the FLS is triggered at the rising edge (F = 1) or at the falling edge (F = 0) and the corresponding values F1 = 1 or F2 = 1 are entered through the states S9 and S10, which activates the condition (F3 = 1) to go to state S6;

– in state S6, the measurement error level L is checked to achieve the maximum permissible values of the hydrostatic sensor. If the measurement error level L is equal to or less than the maximum permissible threshold P1 (P1> = L), then the HLS is in the operating state (ErHLS <= ‘0’), however, if the measurement error level L is greater than the maximum permissible threshold P1 (P1 < L), then the HLS is in the fault state (ErHLS <= ‘1’);

– in state S7 the number of errors of the hydrostatic pressure sensor is counted, and at each error (ErHLS = 1) its value C1 is increased by 1;

– completion of diagnostics of the hydrostatic sensor occurs in state S8, where the conditions of transitions (F1, F2, F3, F4) are reset to zero,

[28] Green Experiments with FPGA. In: Green IT Engineering: Components, Networks and Systems Implementation. Drozd A., Kharchenko V., Kondratenko Y., Kacprzyk J. (Eds.). Springer, 2017, P. 219–239.

after which the work of the FSM diagram starts again from state S1 until Reset (Power = 1) is triggered.

The results of computer simulation of the proposed technical diagnostics of level sensors are presented in the time diagrams (fig. 16).

Simulation of technical diagnostics is carried out in case of faulty operation of HLS. All signals of the FSM diagram are modeled digitally and are connected to the CLK pulse generator.

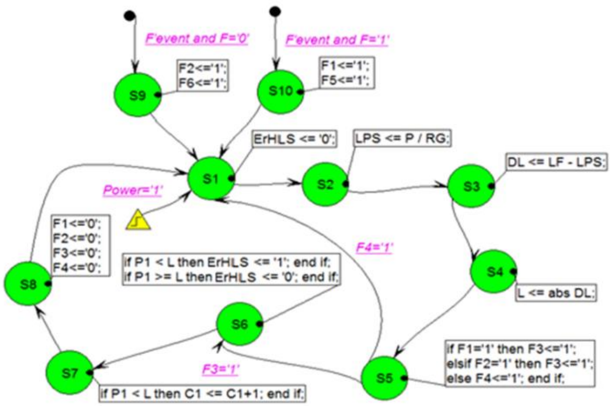


Fig. 15. VHDL Model for technical diagnostics of level sensors

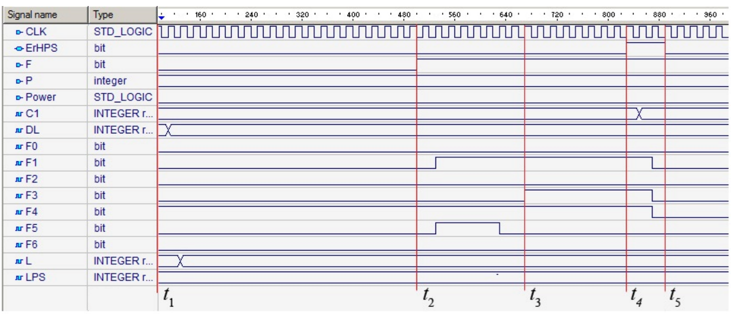


Fig. 16. Modeling of digital signals of technical diagnostics of HLS

In the time $t_1 - t_2$ there is a constant operation of the sensors during prolonged filling or emptying of the ballast tank, namely the value of the hydrostatic pressure sensor is measured, and the discrete level sensor remains unchanged. At times $t_2 - t_3$, the previous actions are performed as a result of the cycle under the condition F4 = 1. At times $t_3 - t_4$, the condition F3 = 1 is set, and the comparison of the registered electrical signal from the hydrostatic pressure sensor and the corresponding current value of the liquid level LF in the ballast tank begins. In this case, a hydrostatic pressure sensor failure is detected (ErHLS <= '1'), since P1 < L, the error is indicated in the sensor error counter, increasing C1 by one. The end of the simulation of technical diagnostics is accompanied in time $t_4 - t_5$ by resetting the conditions F1 <= '0', F3 <= '0' and resetting the error level ErHLS <= '0'.

4. Software and hardware implementation of a computer system for monitoring operational parameters during submersion and surfacing of a floating dock

Developed a special multifunctional computerized system based on remote monitoring and control principles using multiprocessor devices and SCADA software[29] for control of level and physical parameters of liquid products in ballast floating docs. This system is built based on a modular (variable-configuration) structure and has a separate distinct system of remote technical diagnostics using cloud-based ThingSpeak technology.

The functional structure of computerized intellectual system of monitoring and control of fluid level is shown in fig. 17.

Each tank of the floating dock is equipped with pressure sensor PS, three temperature sensors TS, one discrete level sensor FLS (or float level switch), hydrostatic pressure sensor HLS and an input IV and output OV valve.

Level sensors and temperature sensors are used to obtain information of current level L and water temperature T in ballast tanks. A discrete level sensor is required for fixing a certain level value. The pressure sensor PS serves to determine the presence of excess pressure P inside the tanks.

Output signals from sensors are transmitted to the data acquisition module (DAM), which transforms analog signals to the corresponding digits that are transmitted to the PLC (Programmable Logic Controller). The PLC contains a program unit for calculating the dataset parameters, a program unit for liquid volume calculation, and a program control unit for valves. All of them are implemented using specialized SCADA TRACE

[29] Stojkovic, B., Vukasovic M. A New SCADA System Design in the Power System of Montenegro – ICCP/ TASE.2 and Web-Based Real-Time Electricity Demand Metering Extensions. In: Abstracts of the Power Systems Conference and Exposition, Atlanta. 2006, P. 2194-2199

MODE software[30]. The information about current values of the liquid level L in each ballast tank of the floating dock is displayed on the operator's computer screen (OTS) using a specialized human-machine interface.

The human-machine interface allows an operator to control input and output valves for filling and emptying the ballast tanks by controlling the flow Q. Control signals arriving from the OTS are processed in the program control unit for valves and sent to the discrete output module (DOM). In turn, DOM implements the distribution of discrete signals which means the opening and closing of IV and OV.

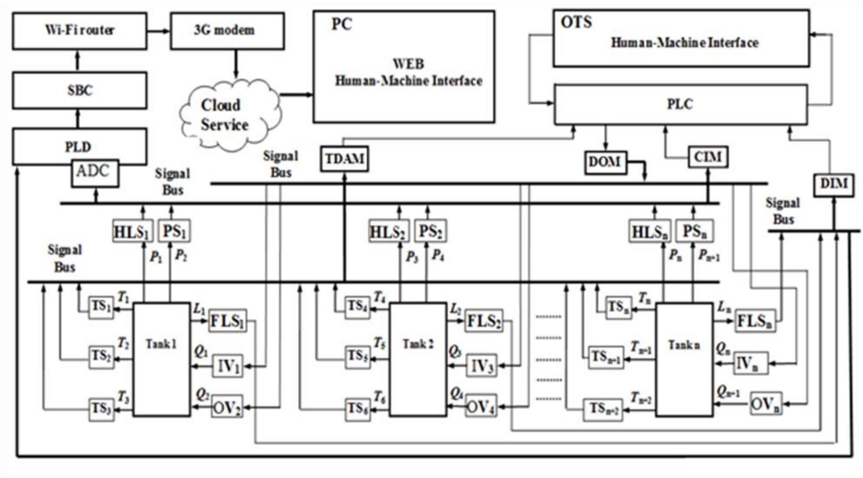


Fig. 17. The functional structure of intellectual computerized system of monitoring and control of fluid level

This computerized system of monitoring and control of ballast tanks' parameters is also equipped with a computerized intelligent system for remote diagnostics of level sensors. The diagnostics equipment should include discrete level sensors, PLD along with an analog-digital converter ADC, single-board computer, WiFi router, 4G modem, and ThingSpeak cloud service.

Data from hydrostatic and discrete sensors are processed using a programmable logic device PLD with FPGA architecture, which, according to specific VHDL models, determines state of the hydrostatic and discrete

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[30] I. Efimov, and D. Soluyanov, SCADA-system Trace Mode, Ulyanovsk: UlGTU, 2010, 158 p. (in Russian).

sensor. The diagnostics computing equipment should include the PLD, a single-board computer, WiFi router, 4G modem, and cloud service ThingSpeak. Diagnostics information from PLD is processed by a single-board computer that transmits data through the Internet network to the ThingSpeak cloud service. Moreover, the Internet on a floating dock is provided by a 4 G modem with the help of global wireless mobile technology 4G (data transfer rate up to 1 Gbit / s) and distributed on the floating dock premises using a WiFi router and additional WiFi access points. The general results of the remote diagnostics system for level sensors are displayed in the ThingSpeak graphically in real-time on any computer or mobile device that specialized in these tasks and had access to the Internet.

Thus, in the ThingSpeak service, one channel was used to send and store technical diagnostics data of two-level sensors (hydrostatic and discrete). The fig. 18 shows the process of technical diagnostics of level sensors in real-time. The left side shows the operation of the hydrostatic pressure sensor, which, as depicted on the screen during its operation, switched to a non-operating state, the level of the red line changed (0 → 1). From the right to properly demonstrate the working sensor at the full time of its ex-operation, the red line is unchanged (0 → 0).

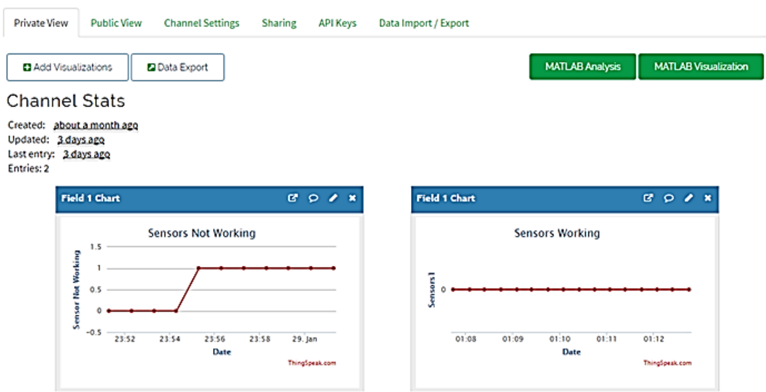

Fig. 18. Web interface of technical diagnostics of level sensors in the ThingSpeak

It should be noted that the computer system of the floating dock must be reliable and must have automatic switching to redundant components and networks of the general system («hot standby»). In this case, the system is considered a part of an experimental model without redundancy, but when implementing such a system for floating docks, redundancy issues must be considered.

Algorithms for measuring and controlling the operational parameters of the floating dock in the PLC are implemented using the tools provided by the TRACE MODE 6 SCADA system, which is a universal and compact SCADA system (all system editors are called from one program). The human-machine interface of this system is implemented using the tools provided in the basic version of the TRACE MODE 6 SCADA system. The developed human-machine interface of the SCS of the experimental floating dock is multi-window. The main SCS screen is shown in fig. 19.

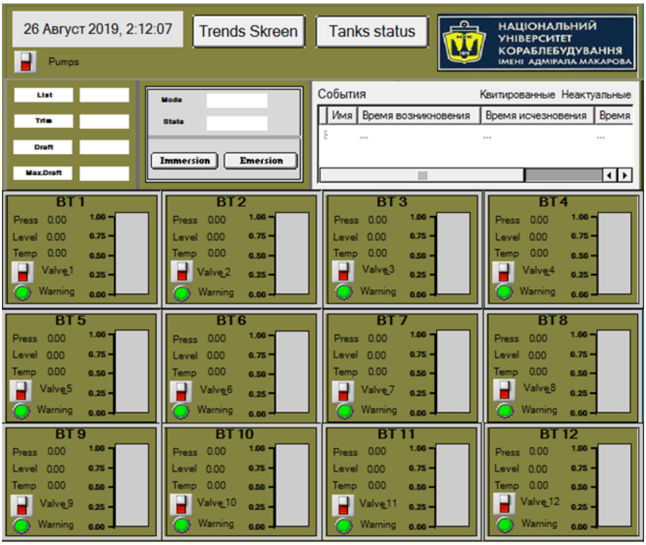

Fig. 19. Human-machine interface of the floating dock parameters control computer system

The main screen provides visualization of the main indicators of the computer system of floating dock parameters control on the operator’s display: List – list angle value; Trim – trim angle value; Deflection – hogging/sagging value; Draft – draft level; Level – water level in the ballast tank; Press – water pressure in the ballast tank; Temp – temperature in the ballast tank; valve – clinker; Immersion – floating dock submersion mode; Emersion – floating dock surfacing mode. The value of the Warning indicators depends on the critical liquid level.

The main screen of the human-machine interface has an information and control panel and a diagram of the location of ballast tanks. The information and control panel contains data on the list, trim, draft, mode and state of operation of the floating dock during submersion and surfacing. Also on the main screen there is an events screen designed to display various situations recorded by the «Events» class channels, their real-time viewing and coloring. For informativeness, the «Events» panel contains tools for setting the color of the line in the absence, appearance and disappearance of an event. On the main screen of the human-machine interface, buttons for quick transition to other screens have been added. Using the «Tanks status» button, the operator can get more detailed information about the filling levels of ballast tanks. The status panel of ballast tanks levels is shown in fig. 20.

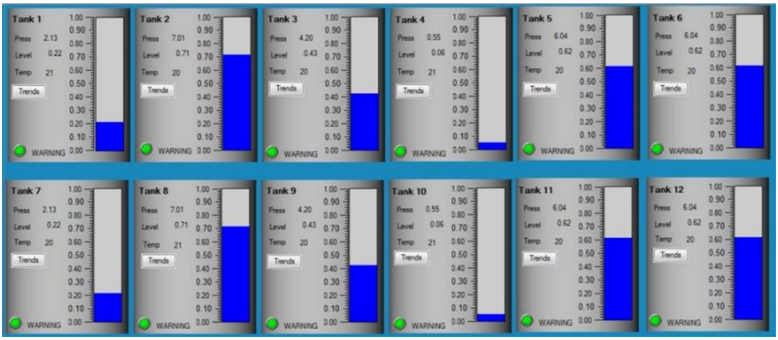

Fig. 20. Panel of ballast tank levels status

Using the «Trends screen» button, the operator has the opportunity to observe the dynamics of the controlled processes on the trend screen. The trend screen graphically displays information about list and trim angles, hogging/sagging of the floating dock, draft and level in ballast tanks. An example of a trend for ballast tank level is shown in fig. 21 (other trends have a similar visual display but with their own indicators).

The general model of interaction between the operator and the computer system for monitoring the parameters of the floating dock includes the main human-machine interface of the SCADA-system and two human-machine interfaces for remote monitoring of the floating dock parameters and for remote technical diagnostics of the HLS sensors.

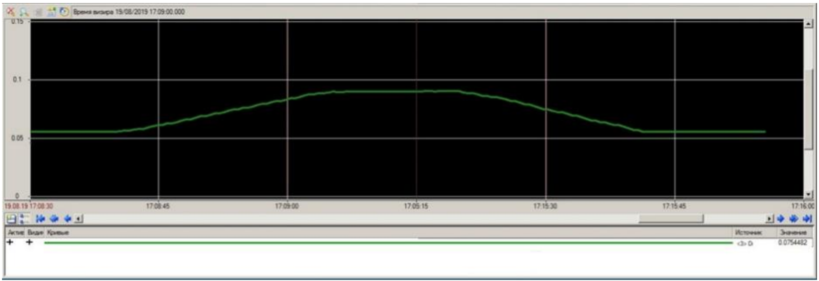

Fig. 21. Trend of level control in the ballast tank

CONCLUSIONS

1. The layout of the floating dock sensor complex is proposed. The hull is equipped with hydrostatic sensors, which are installed evenly with three sensors along the port and starboard sides outside the floating dock, as close as possible to its bottom. Each ballast tank is equipped with a hydrostatic level sensor combined with a temperature sensor located in the center of the ballast tank bottom, an overpressure sensor, a discrete fixed level sensor and a flow meter. This allows for reducing the weight and dimensions of the equipment, expanding the measurement range, and increasing the efficiency and reliability of floating docks operation during dock operations.

2. The method of technical diagnostics of sensor components of the floating dock is improved, which is based on the assessment of the technical condition of the sensors of hydrostatic measurement of liquid level using the developed VHDL-model, which allows to increase the reliability of measurement data and reduce the duration of preventive maintenance of information and measuring equipment.

3. The functional model of SCS of parametric control and controlled stabilization of the floating dock is developed. The use of a computer system with the proposed functional structure makes it possible to monitor and control the main parameters of the floating dock in real-time with sufficiently high accuracy. In addition, the use of cloud technologies expands the capabilities of the proposed system. The developed functional structure guarantees the flexibility and scalability of this monitoring and control system, and therefore it can be easily integrated into large systems and implemented into existing monitoring systems for floating docks, cranes, etc.

4. The developed hardware and software and human-machine interfaces for the multifunctional system of remote control of the floating dock parameters allow to display of all the necessary information on the

operator’s screen and to control of the actuators accordingly. In addition, in the event of an emergency, the system provides the ability to detect it based on the developed algorithms for controlling the operating ranges of the main parameters of the floating dock in real-time. Information on current system parameters and dynamics of their changes is displayed on graphic screens, where each of the controlled parameters is available to the operator.

SUMMARY

Conducting docking operations is a complex technical task, as such operations require (a) continuous monitoring of all operating parameters with highaccuracy and (b) timely control of executive mechanisms in the mode real time. Increasing the productivity and reliability of dock operations is possible due to the creation of new and modification of existing specialized computer systems parametric control and controlled stabilization of floating docks. The work considers the components of the ballast system of the floating dock. The necessary set of sensors of the specialized computer system of the floating dock was selected and a method of technical diagnostics of hydrostatic sensors based on the VHDL model was developed. The synthesis and optimization of intelligent computer control components was carried out, in particular, the information subsystem of the analysis of ballast distribution for the tasks of stabilizing a floating dock during docking operations of submersion and surfacing. A functional model of a specialized computer system of parametric control and controlled stabilization of a floating dock has been developed. On the basis of the functional model, hardware-software and human-machine interfaces for a multifunctional system of remote control of floating dock parameters are proposed.

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