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Information System for Automatic Planning of Liquid Ballast Distribution

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Abstract

The paper is dedicated to the development and study of information system for automatic planning of liquid ballast distribution. The given computer system allows to calculate the current values of the operating variables of the ballast systems of floating structures and vessels of various types when performing different technological operations in the real time mode. The developed algorithmic support and software as well as human-machine interface of the information system gives the opportunity to obtain current information about the operating parameters of the ballast systems when controlling the distribution of ballast in various operating modes of the floating structures. The effectiveness study of the proposed information system for automatic planning of ballast distribution is conducted on the example of a real floating dock. The obtained calculation results confirms the effectiveness of the developed information system.

Keywords

Information system, Algorithmic Support, Human-machine interface, Floating structures and vessels, Ballast system, Ballast distribution

1. Introduction

Ballast systems are used to receive, pump and remove overboard water ballast. Ballast (seawater) is taken on board to a vessel or floating structure to increase draft, to align the list or trim, to change the overall stability.

In general, the ballast system consists of pipelines and pumps for receiving and pumping liquid ballast to perform the necessary ballasting, as well as to align or create an artificial list (list system) and trim (trim system) when performing cargo handling, floating in ice, in emergencies, etc. [1-5].

The ballast system is designed to fill ballast tanks with water. Ballast in dry cargo vessels is approximately 15-20% of the tonnage, and in tankers – up to 50% and more, for floating structures this value may be higher depending on the purpose of the floating structure. The double-bottom tanks are used as ballast tanks, on-board and deck tanks, and on tankers – cargo or special ballast tanks.

The main elements of the ballast system are specialized pumps, pipelines (openflow, outflow and distribution), all kinds of shut-off valves. In practice, different circuits of ballast systems are used, the most common are two basic circuits: linear and circular. In the linear scheme each ballast pump is arranged one on one side and connected to a distribution box, which distributes the processes with the corresponding gate valves to the ballast tanks. The distribution boxes themselves are interconnected by linear pipelines with gate valves. The linear scheme assumes the pumping of water by the pump of the adjacent junction box in case of failure of any of the pumps. The circuit scheme consists of two side lines connected by at least two jumpers. The line connects the ballast pumps and ballast tanks with the gate valves. This system allows the pump system to pump water from any tank with other pumps in case of failure of part of the pumps on the circuit system.

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The main operational requirement for ballast systems of various types is to ensure that all available ballast pumps or a part of them are pumped out when one or more pumps fail. Possibility of simple and fast start-up or shutdown of individual pumps and, as a consequence, possibility of pumping of water from any tank.

Depending on the pipeline scheme, several pumps are serviced by the ballast system. The types of pumps used are centrifugal and propeller pumps. The performance and number of pumps are selected for the predetermined time of pumping out ballast water and ensuring a certain speed of water movement in the ballast pipeline. It is also desirable to select the pumps so that when the pressure drops, the productivity ("flow rate") at constant speeds and power consumption increases. In these conditions, the pumping of water from the ballast tanks occurs most rapidly.

Floating structure in the course of its operation faces problems of equilibrium. Generally, strong winds, currents, can lead to tilts and damage to floating structures and vessels. To eliminate critical deformation and unwanted angles, ballast calculations are made in advance. These calculations primarily determine the selection of ballast, and the purpose of the calculations is to obtain a distribution of ballast at which the list and the trim are zero and the inflection moment is less than the allowable value for a given floating object. It should be considered that with a large stock of ballast tanks, the inflection moments and angles of list and trim can be completely eliminated by balancing the load due to ballast [6-8].

Operating monitoring of all parameters with high accuracy and timely control of ballast submission in tanks for support absence of dangerous inclinations and big deflection of the floating object are the difficult technical tasks.

Ballast distribution systems need specialized computer systems that allow to collect information of technological parameters, to perform efficient automatic control of liquid ballast distribution, as well as to provide operator interface, database accumulation, etc.

Liquid ballast redistribution requires complicated calculations of liquid flow in pipelines, and it is therefore advisable to develop a information system for automatic planning of liquid ballast distribution. The use of new computer-based control systems based on the principles of distributed control using automated ballast planning software will solve a number of problems described and allow effective monitoring and control of the operational parameters of the draft and stability of floating structures and vessels.

2. Generalized Functional Diagram of the Floating Structure Ballast System

To consider the automation of planning ballast distribution in different floating structures, a functional structure of a ballast system is formed. The functional structure of the fragment of the ballast system for the i -th ($i = 1 \dots m$) distribution box is shown in Figure 1. The number of distribution boxes of linear or ring circuits is determined depending on the predetermined time of immersion and emersion of the floating structure. Each distribution box serves a specific number of ballast tanks and includes one receiving pipeline for the liquid ballast filling and one discharge pipe with a pump for the liquid ballast emptying. Pipeline outlets of the components of the branched pipeline are connected with the distribution box in each ballast tank of the pontoon. Pipeline fittings are usually presented in the form of automated gate valves, which are placed on the receiving and outflow pipelines and on each branching of the branched pipeline. The distribution boxes are interconnected by pipelines in a circular or linear arrangement with intermediate pipelines with gate valves.

In Fig. 1 the following designations are adopted: $DBBP_1$, $DBBP_i$ are the first and i -th distribution boxes with branched pipeline; $BT_{i,1}$, $BT_{i,2}$, ..., $BT_{i,n}$ are the ballast tanks; P_1 is the ballast pump; RPF_1 is the receiving pipeline for filling; DPD_1 is the drain pipeline for devastation; TP_1 is the trunk of the pipeline; BP_i is the branched pipeline; $BP_{i,1}$, $BP_{i,2}$, ..., $BP_{i,n}$ are the branches of BP_i ; VPF_1 is the gate valve of RPF_1 ; VPD_1 is the gate valve of DPD_1 ; $SVPF_1$ is the stop gate valve of RPF_1 ; $VBP_{1,1}$, $VBP_{1,2}$, ..., $VBP_{1,n}$ are the gate valves of BP_1 (each gate valve includes a power converter, drive motor, gearbox and shutter); $SVPD_1$ is the stop gate valve of DPD_1 ; CP_1 is the common pipeline; VCP_1 , VCP_2 are the stop gate valves of CP_1 ; There are following computer control signals in Fig. 1: u_{VPF_1} , u_{VPD_1} , u_{SVPF_1} , u_{SVPD_1} , $u_{VBP_{1,1}}$, $u_{VBP_{1,2}}$, ..., $u_{VBP_{1,n}}$ – for VPF_1 , VPD_1 , $SVPF_1$, $SVPD_1$, $VBP_{1,1}$, $VBP_{1,2}$, ..., $VBP_{1,n}$; u_{VCP_1} , u_{VCP_2} – for VCP_1 and VCP_2 ; u_{AM1} , f_{AM1} are the asynchronous motor's pump P_1 voltage and control frequency (usually, coming from frequency converter, computer generates setting values). Finally, the following

physical (technical) parameters are shown in Fig. 1: S_{VPF1} , S_{VPF2} , S_{VPD1} , S_{VPD2} , $S_{VBP1,1}$, S_{VCP1} , S_{VCP2} , $S_{VBP1,2}$, ..., $S_{VBP1,n}$ are the plane surfaces of involved gates of respective gate valves VPF₁, SVPF₁, VPD₁, SVPD₁, VCP₁, VCP₂, VBP_{1,1}, VBP_{1,2}, ..., VBP_{1,n}; Q_{F1} is the flow of ballast liquid when filling at the inlet of DBPP₁; Q_{E1} is the flow of ballast liquid when emptying at the output of the distribution box; Q_{FTP1} is the flow of ballast liquid when filling at the inlet of TP₁; Q_{ETP1} is the flow of ballast liquid when emptying at the output of TP₁; Q_{EP1} is the flow of ballast liquid when emptying at the output of P₁; $Q_{FBP1,1}$, $Q_{FBP1,2}$, ..., $Q_{FBP1,m}$ are the flows of ballast liquid when filling at the inlet of BP_{1,1}, BP_{1,2}, ..., BP_{1,n}; $Q_{EBP1,1}$, $Q_{EBP1,2}$, ..., $Q_{EBP1,n}$ is the flow of ballast liquid when emptying at the output of BP_{1,1}, BP_{1,2}, ..., BP_{1,n}; $Q_{FBT1,1}$, $Q_{FBT1,2}$, ..., $Q_{FBT1,n}$ are the flows of ballast liquid when filling at the inlet of BT_{1,1}, BT_{1,2}, ..., BT_{1,n}; $Q_{EBT1,1}$, $Q_{EBT1,2}$, ..., $Q_{EBT1,n}$ are the flows of ballast liquid when emptying at the output of BT_{1,1}, BT_{1,2}, ..., BT_{1,n}; Q_{ETP1} is the flow of ballast liquid when emptying at the output of the TP₁ to CP₁; Q_{FTP1} is the flow of ballast liquid when filling at the inlet of TP₁ from CP₁; L_{BT} , V_{BT} , m_{BT} are the level, volume and mass of ballast liquid in the BT_{1,1}, BT_{1,2}, ..., BT_{1,n}.

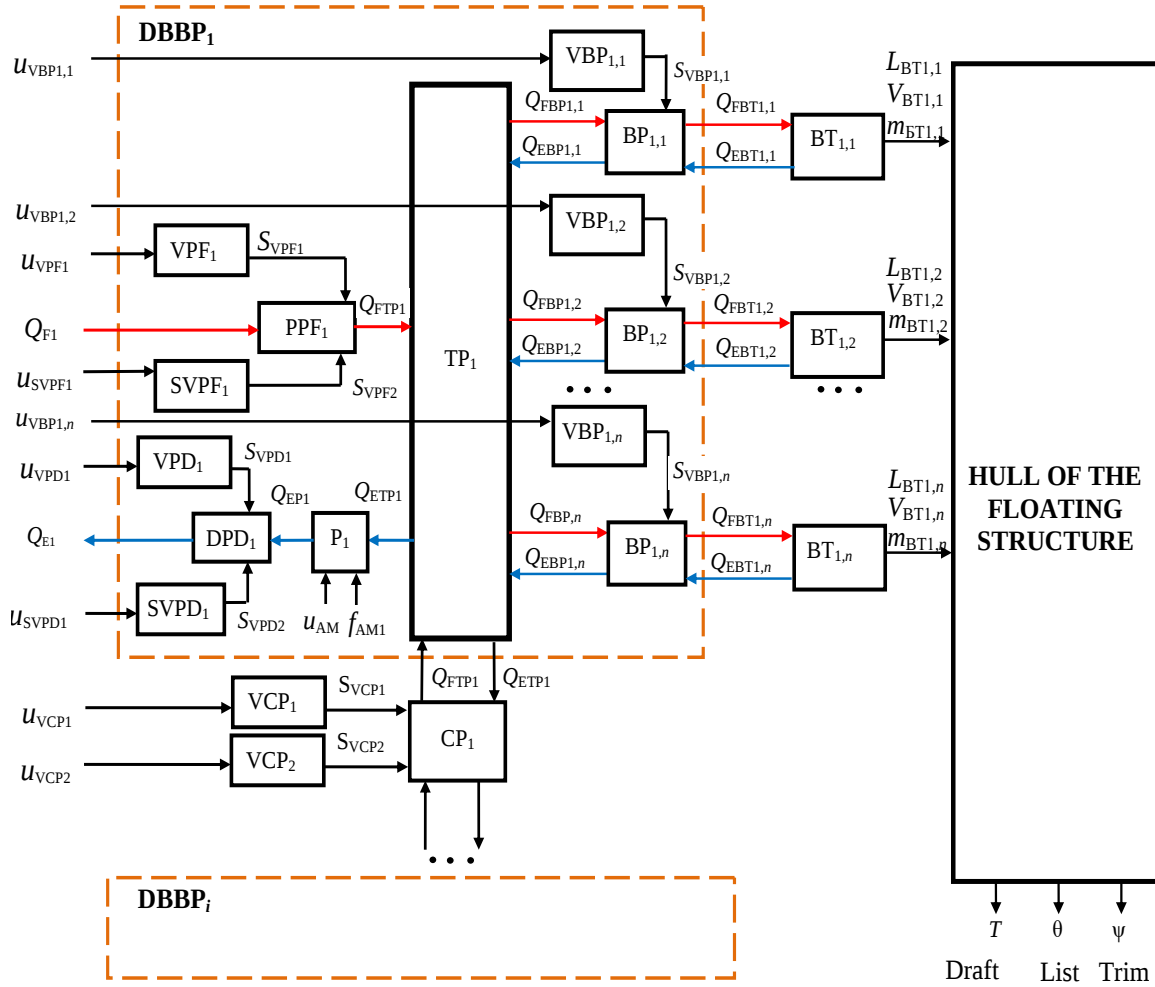


Figure 1: Functional Diagram of a Part of the Floating Structure Ballast System (red line is the direction of liquid motion when filling ballast tanks, blue line is the direction of liquid motion when ballast tanks emptying)

Filling of BT_{1,1}, BT_{1,2}, ..., BT_{1,n} occurs naturally (due to the action of gravity on the floating structure and outboard inlet openings for liquid intake). Emptying of BT_{1,1}, BT_{1,2}, ..., BT_{1,n} is carried out by means of the centrifugal pump P₁ (removal of liquid beyond the floating structure through the outflow openings). Both filling and emptying processes are performed separately and serve mainly for dipping and floating operations (e.g. floating docks), as well as for stabilizing list and trim angles (floating hotels, drilling platforms, coastal power plants).

Regardless of the filling or emptying of the ballast tanks of the floating structure, flow rate control is performed by throttling gate valves VBP_i . Gate valves VBP_i implement smooth automatic control of ballast water discharge $Q_{FBT_{i,1}}, Q_{FBT_{i,2}}, \dots, Q_{FBT_{i,n}}, Q_{EBT_{i,1}}, Q_{EBT_{i,2}}, \dots, Q_{EBT_{i,n}}$ depending on control signal u_{VBP_i} (0...10 V). Thus, to fill $BT_{i,1}, BT_{i,2}, \dots, BT_{i,n}$ a positive signal u_{VPF_1} (10 V) is fed to the input of VPF_1 for the corresponding gate opened position, and a zero signal u_{VPD_1} (0 V) is fed to the input of VPD_1 for the corresponding gate closed position, as well signal u_{VBP_i} (0 to 10 V) is supplied to control the filling discharge for the each VBP_i . In turn, a positive signal u_{VPD_1} (10 V) is fed to the input of the VPD_i for the corresponding gate open position, the zero signal u_{VPF_1} (0 V) is fed to the input of the VPF_1 for the corresponding gate closed position, the pump P_1 is switched to the nominal mode ($u_{AM1} = u_{nom}, f_{AM1} = f_{nom}$), as well signal u_{VBP_i} (0 to 10 V) is supplied to control the filling discharge for the each VBP_i .

The generalized functional structure of the floating structure ballast system may be completed with additional intermediate pipes with gate valves between the distribution boxes, depending on the circuit of the ballast pipeline (ring or linear). The structure may consist of several distribution boxes $DBBP_1, \dots, DBBP_i$ connected by pipelines (an example of one distribution box is presented in Fig. 1). In our case, the common pipeline CP_1 is used to connect the junction boxes with stop gate valves VCP_1 and VCP_2 to control of the flows Q_{FTP_1}, Q_{ETP_1} . And gate valves VCP_1 and VCP_2 are controlled by signals u_{VCP_1}, u_{VCP_2} (0 to 10 V). The distribution boxes work separately from each other, but in case of failure of one of the distribution boxes, another distribution box can perform its function through an adjacent pipeline.

3. Peculiarities of Flow Calculation in a Ballast System Pipeline and Algorithmic Support of Information System for Automatic Planning of Ballast Distribution

Processes for filling or emptying ballast tanks occur through a complex ballast pipeline having variable length and branches. And the place of the pipeline, where several pipe connections are connected, is called nodes. This pipeline contains both serial and parallel connections [9-11].

The serial pipeline consists of two pipes of different lengths and diameters. If we note the total flow rate through Q it is obvious that

$$Q = Q_1 = Q_2, \quad (1)$$

where Q_1, Q_2 are the flow rate for two pipes.

$$h = h_1 + h_2. \quad (2)$$

where h_1, h_2 are the loss of pressure for two pipes

The parallel arrangement of pipes of different lengths and diameters are connected at the junction of the trunk. If we note the total flow rate through Q it is obvious that

$$Q = Q_1 + Q_2. \quad (3)$$

Pressure losses are equal:

$$h = h_1 = h_2. \quad (4)$$

The structure of a complex pipeline of a junction box with a branched pipeline of a ballast system can be presented in Figure 2. In this pipeline considered piezometric pressure H_0, H_1, H_2, H_3, H_n and flow rate Q_0, Q_1, Q_2, Q_3, Q_n , in particular in the main pipeline pressure H_0 , flow rate Q_0 , in the node pressure H_1 , flow rate Q_0 and on branched sections of pipes pressure H_2, H_3, H_4, H_n , flow rate Q_1, Q_2, Q_3, Q_n .

To determine the flow rate in the main pipeline Q_0 and in the components of the branched pipeline Q_1, Q_2, Q_3, Q_n provided that $H_0 > H_1 > H_2, H_1 > H_3, H_1 > H_4, H_1 > H_n$, take advantage of the Bernoulli equation and the equation for the conservation of flow rate (or continuity).

The continuity equation in this case will look like this

$$Q_0 = Q_1 + Q_2 + Q_3 \dots + Q_n \quad (5)$$

Pressure losses on separate sections of pipelines arising from Bernoulli equations

$$h_1 = H_0 - H_1 = \left(\frac{\lambda l_1}{d_1} + \sum \zeta_1 \right) \frac{16Q_1^2}{\pi^2 d_1^4 2g}. \quad (6)$$

$$h_n = H_1 - H_n = \left(\frac{\lambda l_n}{d_n} + \sum \zeta_n \right) \frac{16Q_n^2}{\pi^2 d_n^4 2g}, n = 2, 3, 4, \dots, j \quad (7)$$

where λ is the coefficient of hydraulic resistance depending on the flow regime, l is the length of the pipeline, d is the diameter of the pipeline, ζ is coefficient of local resistance; g is the acceleration of gravity; l_1, d_1 are length and inner diameter of each pipeline, n is the pipe number.

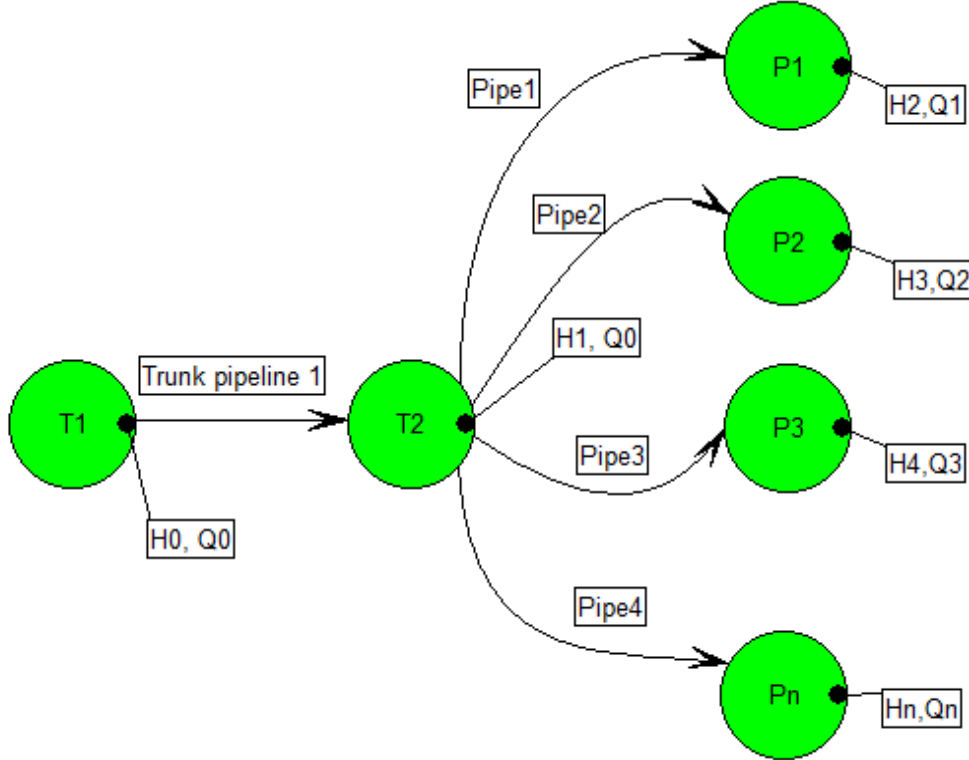


Figure 2: Structure of a Complex Pipeline Distribution Box with a Branched Pipeline

The above equations are combined into a system of equations that relate the required flow and pressure losses in individual sections of pipelines. However, analytically, the problem can be solved in cases where the flow regime can be predicted before the calculation, and thus the type of dependence λ on Re . In the case of unknown parameters, it is better to use a combined method with the construction of pressure-flow characteristics.

Consider a case in which filling and emptying is considered for ballast tanks of floating dock, respectively. The flow of fluid in the pipeline changes direction depending on the filling or emptying of the ballast tanks. When filling, the movement of the liquid ballast is directed to the ballast tanks by gravity. When emptied, the movement of liquid ballast is directed from ballast tanks by means of pumps. Therefore, there are two cases of ballast system operation, the devastation and the filling of ballast tanks [12-18].

The calculation is performed for one consecutive section of the pipeline and five pipeline by means of the software. The values of the pressure and the losses of the pressure of the pipes at the corresponding flow rate are precalculated in the model taking into account the resistance of the pipelines. The given model operates as follows. The constant increase in flow rate unit generates a signal of gradual increase in flow rate, from which the pressure determination unit is calculated in the pressure with the corresponding flow rate (in the case of constant pressure, the pressure value does not change). Also, losses in pipelines 1, 2, 3, 4, 5 are determined from the total flow rate. Thus, for each pipeline, the pressure loss is determined depending on the friction and local resistances in the pipe. Moreover, the values of local resistances depend on the positions of gate valves, which may change with each new calculation [19-23].

Figure 3. shows the algorithm for determining pressure loss in a complex pipeline. The algorithm starts with obtaining the values of the pressure in the pipeline. Next, the pressure-flow characteristics of the source pressure, branching pipes and line are calculated. The next step is to obtain the total pressure-flow characteristics of the ramified section and the entire pipeline. Then the flow is determined in the trunk pipeline and in the branched pipes. After receiving the flow rate information, the ballast tank filling time is calculated. The algorithm finishes recording all flow rate data.

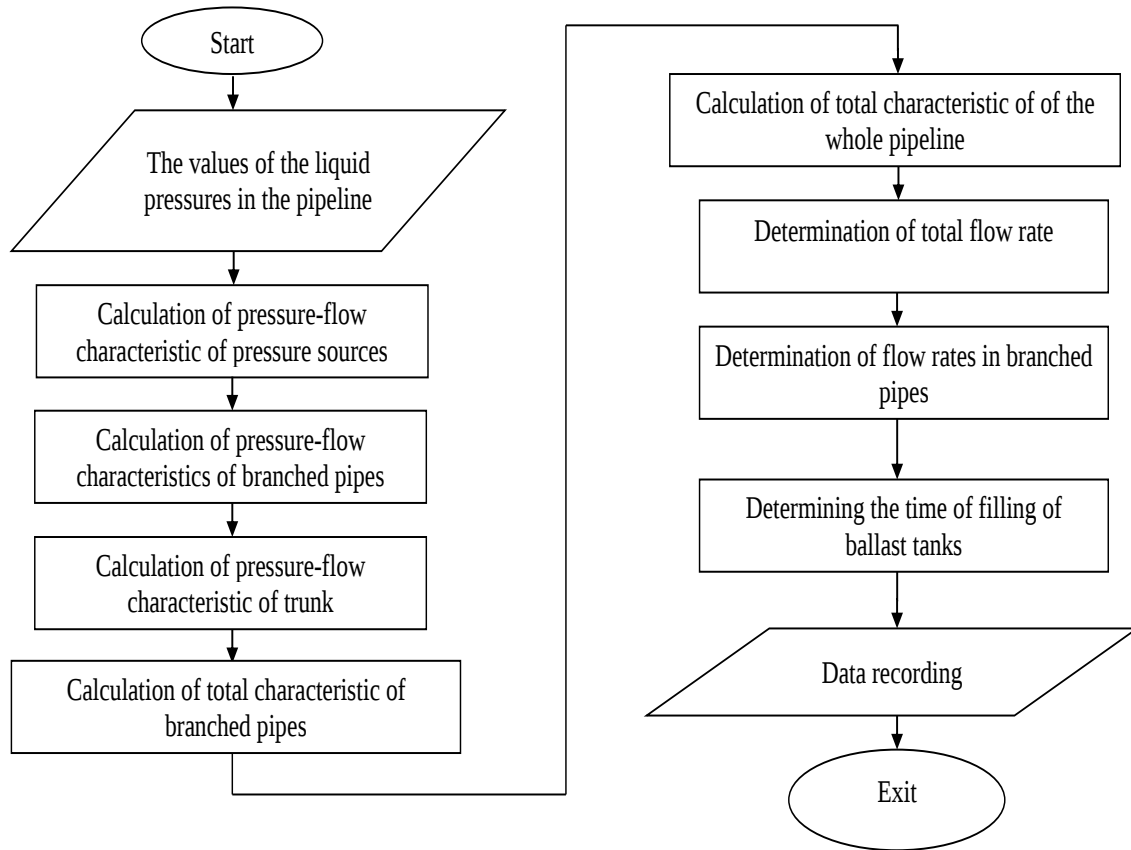


Figure 3: Algorithm for Determining Pressure Loss in a Complex Pipeline

Indirect calculation of ballast compartment parameters in the proposed algorithm is performed using a graph-analytic method of determining flow rate in a complex pipeline implemented in MATLAB. The algorithm contains operations of data analysis from graphs, which requires performing table interpolation of data arrays. MATLAB programming language is best suited for these purposes, since its functions are intended for the analysis and processing of data given in the form of numerical arrays, which precisely describes the hydrodynamic parameters of the ballast system. MATLAB makes writing programs and algorithms faster than traditional programming languages, because there is no need to declare variables, determine types, and allocate memory, and therefore reduce the time required to solve the proposed application problem.

4. Software Implementation and Testing of Information System for Automatic Planning of Ballast Distribution

The information system for automatic planning of ballast distribution is built using MATLAB programming and integrates a functional hydraulic parameter calculation model and an algorithm for determining flow rate in a complex pipeline. The output of the computer system's performance is displayed in the GUI of the software application. GUIs are graphical windows containing controls (buttons, lists, switches, labels, scrollbars, input areas, menus), as well as text areas for outputting.

Creating a graphical interface includes the following basic steps: the location of the required interface elements within the graphical window and programming events that occur when the user accesses these objects, for example, at the click of a button [24-31].

The graphic interface of the synthesized information system for automatic planning of ballast distribution for 5 tanks is presented in Figure 4. The user (operator) has the ability to install various configurations of ballast tanks and set the parameters of fluid flow in a complex pipeline. For this, the interface of the Information System for automatic planning of liquid ballast distribution provides a separate area for configuring ballast tanks by drawing them and specifying geometric dimensions. Also, in this way, the operator has the opportunity to create his own library of options for the configurations of ballast tanks.

Let's consider the impact of placement and weight of liquid cargo on the example of a floating dock with a carrying capacity of 8500 tons. The ballast system consists of four distribution boxes, 20 ballast tanks and is equipped with ballast pumps with a capacity of 3750 m³/h. Centrifugal type pumps, in turn, operate at a constant speed. The receiving pipelines have a diameter of 750 mm, the branched ballast pipeline has a diameter of 350 mm. All gate valves have motor reducers of 2-10 kW.

Calculation of distribution box operation for 5 ballast tanks

Resistance coefficient of pipeline fittings	Flow rate of pipeline sections
z_1 0	$Q_{all} =$ l/s
z_{2_1} 0	$Q_{2_1} =$ l/s
z_{2_2} 0	$Q_{2_2} =$ l/s
z_{2_3} 0	$Q_{2_3} =$ l/s
z_{2_4} 0	$Q_{2_4} =$ l/s
z_{2_5} 0	$Q_{2_5} =$ l/s

Time of filling/emptying tanks in the pontoon
$time_{all} =$ h
$time_{2_1} =$ h
$time_{2_2} =$ h
$time_{2_3} =$ h
$time_{2_4} =$ h
$time_{2_5} =$ h

Schematic Diagram: A vertical arrangement of five ballast tanks labeled BT1, BT2, BT3, BT4, and BT5. BT1 is at the bottom, followed by BT5, BT4, BT3, and BT2 at the top. A pump is located to the right of the tanks, connected to the pipeline system.

Figure 4: Graphic Interface of Information System for Automatic Planning of Ballast Distribution for 5 Pontoon Tanks

In Figure 5. The dependence of the flow rate on the hydraulic resistance of one of the 5 valves of a complex pipeline is presented. This graph shows how much the water flow in each of the pipelines will change when the damper on the first pipeline is completely closed and the dampers on the other pipelines are fully open. Consequently for the simultaneous filling of different ballast tanks, it is necessary to calculate coefficients of hydraulic resistance for each section of the ballast tank pipeline. The simulation was considered for the case of filling of five ballast tanks of a floating dock at one time, with an estimated filling time of 1.3 h., 1.7 h., 2.1 h. The calculations results are presented in table 1.

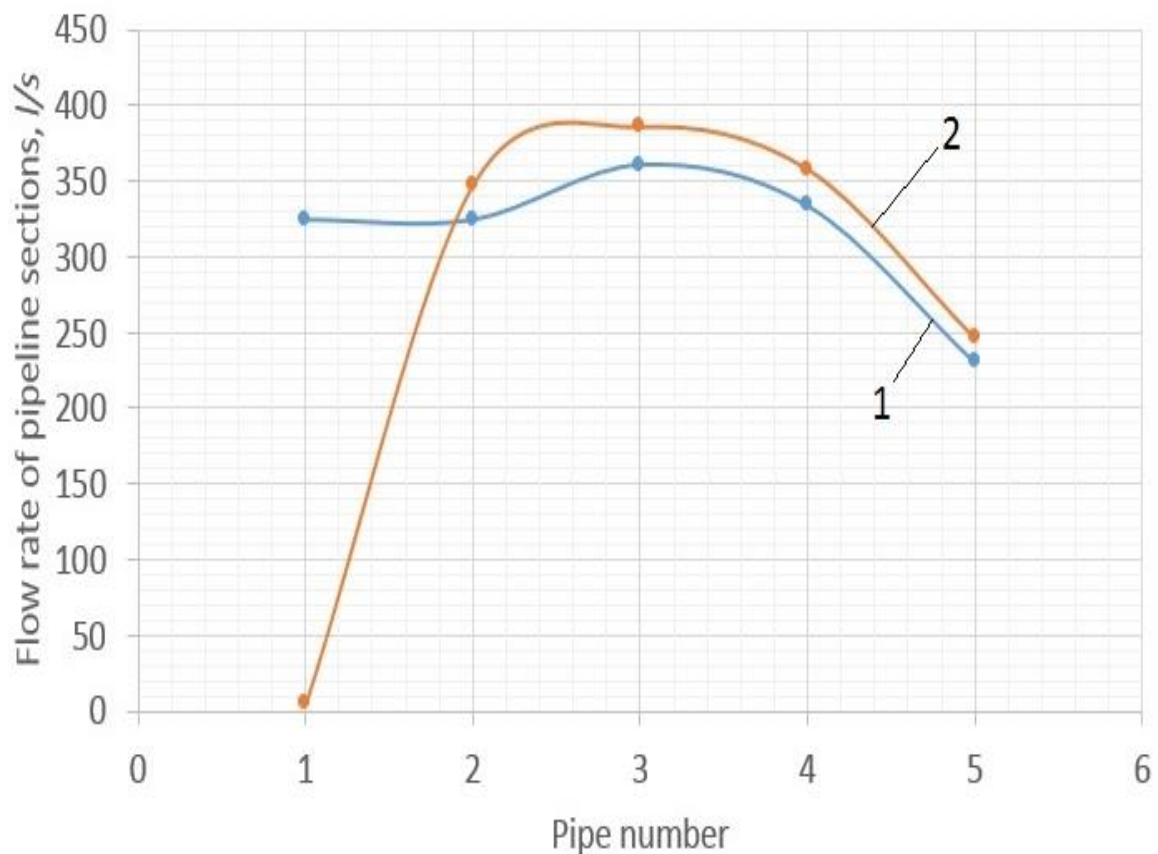


Figure 5: Graph of flow dependence on the hydraulic resistance of the valve of first pipe in the complex pipeline: 1) The value of the flow rate with fully open valves ($\zeta=0$) of the pipeline; 2) The value of the flow with the closed valve ($\zeta=2000$) of the first pipeline and fully open valves on other pipelines

Table 1

Results of calculations of coefficients of hydraulic resistance of gate valves at filling 5 pontoon ballast tanks within 1.3 h

	BT volume V, m^3	Length of branched pipeline of appropriate BT, m	Diameter of the pipeline for appropriate BT, m	Hydraulic resistance ζ for the gate valve of the corresponding BT at filling within 1.3 h	Hydraulic resistance ζ for the gate valve of the corresponding BT at filling within 1.7 h	Hydraulic resistance ζ for the gate valve of the corresponding BT at filling within 2.1 h
BT1	637,91	5,8	0,35	13	25	40
BT2	1012,5	5,8	0,35	4	9	15
BT3	553,28	3,67	0,35	18	35	50
BT4	1139,1	10,8	0,35	3	7	12
BT5	1260,3	25,7	0,35	0	3	7

According to the simulation of information system for automatic planning of ballast distribution, it can be seen that the change in the hydraulic resistance coefficient of one pipeline affects the flow rate values in all pipeline sections. For the simultaneous filling of various ballast tanks housed in the

pontoon, the following hydraulic resistance coefficient ζ of the flow regulators (gate valves) are required: BT1 – 13, BT2 – 4, BT3 – 18, BT4 – 3, BT5 – 0.

5. Conclusions

In this paper the authors consider development and study of information system for automatic planning of liquid ballast distribution. The given computer system gives the opportunity to calculate the necessary current values of the operating variables (flow rates and coefficients of hydraulic resistance of gate valves) of the ballast system when performing different technological operations (draft changing, list or trim aligning, changing the overall stability) of floating structures and vessels of various types in the real time mode.

Developed algorithmic support and software of the information system allow to use analytical and graph-analytical methods of calculation of filling and emptying processes of ballast system on the basis of the Bernoulli equation and pressure-flow characteristics for accurately determining the required parameters of the liquid ballast distribution. The developed human-machine interface of the given system allows the operator to visually obtain current information about the operating parameters of the ballast system when controlling the distribution of ballast in various operating modes of the floating structure.

A study of the effectiveness of the proposed information system for automatic planning of liquid ballast distribution is carried out when calculating the parameters of the ballasting of the floating dock with capacity of 8500 tons while filling its certain tanks in a fixed time (1.3 h., 1.7 h., 2.1 h.). The obtained results in the form of necessary values of hydraulic resistance coefficients and flow rates of the gate valves of the corresponding ballast tanks have a sufficiently high accuracy, which confirms the effectiveness of the developed information system.

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