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Thrust allocation system for Blue Lady training ship taking into account efficient work of main propeller

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Abstract
Thrust allocation system combines the work of an automatic control system with the ships actuators. On the basis of values of transversal and longitudinal forces and yaw moment determined by the regulator, it specifies commands for the individual thrusters located on board. A modified power distribution system, which takes into account the efficient work of a main engine propeller, is presented. During the research computer simulations were made on the basis of a modified and an unmodified thrust allocation system working with an LMI controller and a mathematical model of a training tanker. "Proposed method" of power distribution results in more efficient work of the controller and guarantees faster determination of the fixed velocity value.

Introduction

Thrust allocation system determines the optimum values of each propellers thrust, and when the ship's propulsion system contains azimuth thrusters (rotating ones) – it also assigns the angle of rotation depending on the force and moment values acting on the model. Allocation system is directly related to the control system and the controlled object. Figuratively, it can be indicated that it goes between the regulator and vessel, which is shown in the figure 1.

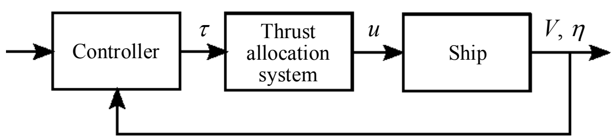

Fig. 1. Block diagram of control system with propeller and thrusters allocation system and controlled object

The use of power distribution system in ships automatic control allows for controller acceleration and lightening its load. The controller requires significantly less computing power in the process of its operation, which is described in the dimension of the output signal vector. Its layout is designed directly for a particular application, namely the type of vessel (number of the degrees of freedom) and the amount and type of used thrusters (azimuth or with fixed angle of action) [1]. In [2] systems designed for a ship with three propellers are shown. Whereas in [3] a submarine with five thrusters is shown. In the positions mentioned above thrust allocation differs significantly depending on the amount of used thrusters and the type of vessel on which they are operating.

Thrust allocation between the propellers can be interpreted as a nonlinear optimization problem with constraints. The equations and constraints are defined depending on the number of degrees of freedom and the type of propellers. The computational complexity of the problem grows with the increase in the number of degrees of freedom [4]. To ensure proper system operation, it is important to take into consideration the physical constraints of working propellers such as: saturation characteristics of individual thrusters, prohibited sectors, overloading of the power supply system and failure of one or more devices. The simplest form of the optimization problem, which can be used in power distribution to individual thrusters, is a quadratic programming task. Johansen and others described in [5] the method in which constraints for fixed thrusters are linear and for azimuth ones – these constraints are partially linearized. A similar method, except that in addition it takes into account thruster grouping to avoid mutual influence at each other at a certain angle of rotation, was proposed in [2].

Another, but more complex, way is presented in [4]. It is an iterative solving of nonlinear programming problem. In this case function linearization in the vicinity of the operating point is not necessary. However, the disadvantage of this approach is a significant complication of calculations and thereby it lengthens the time and increases demand for processing power.

A different approach that does not require solving of optimization problems is presented by Sordalen in [6]. It is based on equation (1), indicating that the vector containing force values designated by the controller (τ) is connected with the control values (u) through the matrix of individual propeller thrust values (T).

$$\tau = T \cdot u^{1)} \qquad (1)$$

1) Mathematical calculations are significantly simplified by the use of matrix notation.

If thrust matrix (T) is square matrix, in order to designate vector of control values for individual propellers the computation of the pseudo-inverse Moore-Penrose matrix is needed. In this case there is no need to solve computationally complicated nonlinear optimization problems. This solution decreases demand for processing power in a significant way. This approach has been used by Garus in [3] to design the trust allocation system for an underwater vehicle and by Gierusz in [7] to create a power distribution system working with different controllers on a real sailing training ship model – tanker built in scale of 1:24.

Propulsion system of the real sailing training ship model

When controlling the real object, the type and arrangement of thrusters should be taken into account. Real sailing training ship model of a VLCC (*Very Large Crude Carrier*) tanker Blue Lady, which is owned by The Foundation for Safety of Navigation and Environment Protection, is shown in figure 2. On the basis of this ship built in scale of 1:24, the thrust allocation system was designed and tested.

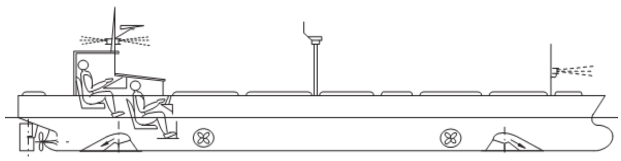

Fig. 2. Blue Lady ship model side view with the location of all thrusters, main propeller, rudder and crew compartment [1]

The ship may be controlled automatically with the use of earlier elaborated algorithms or manually. In both cases there is a possibility to use all thrusters, whose location on board is presented in figure 3.

When the ship is controlled manually physical devices used for manual thrust allocation are located in two places on board. In the upper crew compartment of the steering house the user has access to rudder and main engine propeller control and in the lower crew compartment there is the steering panel for remaining thrusters, which is shown in figure 4. Located there are control levers for bow thrusters (indicated by 2 in Fig. 4) and stern thrusters (indicated by 3 in Fig. 4). In case of bow rotatable thruster (knob indicated by 4 in Fig. 4) and stern rotatable thruster (knob indicated by 4 in Fig. 4) the user controls not only their thrust, but also manipulates their angle of rotation. Angle of propeller with respect to ships axis is set by knob rotation to the desired position. Controlling of thrust value is done by shifting of the metal lever placed in the middle of the rotatable knob. In case of automatic control the same executive devices, to which a person controlling the model has access, are used. However, in this case the manual setting is not read and has no influence on the used algorithm. It is a protection from accidental change of individual propellers thrust during automatic control process.

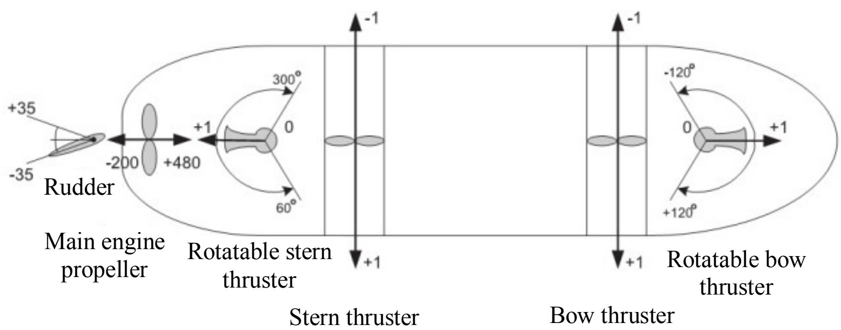

Fig. 3. Location of all thrusters, main propeller and rudder with limit values of control signals [1]

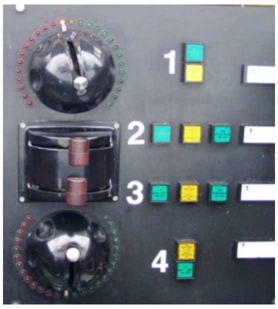

Fig. 4. Control panel with manual controls of all thrusters

Individual thrusters give a possibility of generating forces acting in different directions and twisting moments of different values. Their values are dependent on thruster type and its location relative to the ships pivot point, set points and in case of azimuth thrusters also their angle of rotation. Training ship VLCC (*Very Large Crude Carrier*) Blue Lady has one main engine propeller located astern, just before the rudder. The main task of this propeller is to generate the longitudinal force acting along the ships axis. Forces acting in other directions result from the cooperation of main engine propeller with the rudder blade. Contra propeller is driven directly to the rudder blade. The efficiency of the rudder increases with the increase of water speed acting on it. Bow and stern thrusters are mounted perpendicular to the ships axis. Their task is to produce a lateral force, as well as torque – in connection with their placement at some distance from the ships pivot point. Their effectiveness decreases with the increasing of vessel speed and, therefore, it is beneficial to use them only when manoeuvring at low longitudinal speeds. Rotary thrusters (bow and stern) can be rotated by an angle α around the vertical axis. The effect of their operation is creation of a resultant force, which is dependent on the propellers thrust and the angle of rotation. This force in accordance to the opportunity of vector value decomposition, can be decomposed into a longitudinal and a transverse component. This type of propeller can generate a force acting in any direction, which is often used in a dynamic positioning systems (DP). Therefore, ships rotatable thrusters generate both lateral and transversal forces and also a yaw moment.

In the thrust allocation system all of the actuators to which the control algorithm has direct access should be taken into account. They should be used depending on the desired values of longitudinal and transverse forces and also torque, while taking into account ships speeds at which individual thrusters are effective.

Because of the lack of wind breeze on Silm Lake (where research experiments are carried out), it was assumed that the mathematical model of VLCC Blue Lady tanker model is a simplified model with three degrees of freedom – 3DOF Model. Accordingly, in both, control and power distribution systems, it is taken into account that only longitudinal and transversal forces and torque about the vertical axis, called yaw moment, can occur.

Thrust allocation system

Thrust allocation system ensures distribution of forces and torque among all available thrusters. Its use in conjunction with the controller results in an appropriate division of forces elaborated by the controller between the actuators, which in case of the ships speed control are thrusters. Output signals from the controller are required hydrodynamic thrusts in the longitudinal axis (τ_x), lateral axis (τ_y), and desired torque (τ_p) of the vessel.

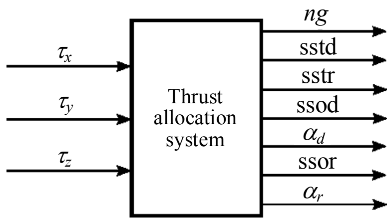

Fig. 5. Input signals τ_x, τ_y, τ_p – forces and torques acting on the ship. Input signals of the allocation system where vectors $[ng, \text{sstd} \ldots]^T$ – are commands for thrusters, where (ng) main propeller, (sstd) bowthruster, (sstr) sternthruster, (ssod) forward rotational thruster, (α_d) angle of forward rotational thruster, (ssor) aft rotational thruster, (α_r) angle aft rotational thruster

In case of application of the power distribution system (Fig. 5) they become input signals, converted according to equation (2) into set points of individual thrusters constituting a command vector Λ [7]. As a result of the calculations carried out in this system instantaneous values of: main engine propeller revolutions (ng), thrust of the tunnel bow thruster (sstd), thrust of the tunnel stern thruster (sstr), thrust of the rotatable bow thruster (ssod), angle of rotation of the rotatable bow thruster (α_d), thrust of the rotatable stern thruster (ssor) and angle of rotation of the rotatable stern thruster (α_r) are received. On the basis of equation (1) i.e. $\tau = T \cdot u$, the following relation was determined:

$$\mathbf{\Lambda} = \mathbf{A}_{al}^{g} \times \mathbf{u} \tag{2}$$

where:

$\mathbf{\Lambda}$ – vector of commands for individual thrusters;

$\mathbf{A}_{al}^{g}$ – pseudo inverse Moore-Penrose matrix of matrix $\mathbf{A}_{al}$ containing the longitudinal and transversal forces and torques from individual thrusters;

$\mathbf{u} = [\tau_x\ \tau_y\ \tau_p]$ – forces and moments acting on the ship.

Matrix $\mathbf{A}_{al}$ in case of the real sailing model of VLCC tanker Blue Lady has a form described by equation (3) [7]. Its values are dependent on the momentary values of the forces acting along the ships axis (marked as x), perpendicular to the ships axis (marked as y) and torques (determined from the known transversal force – y and the distance between the ships centre of gravity and the propeller placement – d) originating from individual thrusters. In case of forces and moments, which can't be produced by the particular propellers zero values are assumed:

$$\mathbf{A}_{al} = \begin{bmatrix} x_{ng} & x_{\text{std}} & x_{\text{str}} & x_{\text{sod}}\cos(\alpha_{dc}) & x_{\text{sor}}\cos(\alpha_{rc}) \\ 0 & y_{\text{std}} & y_{\text{str}} & y_{\text{sod}}\sin(\alpha_{dc}) & y_{\text{sor}}\sin(\alpha_{rc}) \\ 0 & y_{\text{std}}d_{\text{std}} & y_{\text{str}}d_{\text{std}} & y_{\text{sod}}d_{\text{sod}}\sin(\alpha_{dc}) & y_{\text{sor}}d_{\text{sor}}\sin(\alpha_{rc}) \end{bmatrix} \tag{3}$$

where: std – tunnel bow thruster, str – tunnel stern thruster, sod – rotatable bow thruster, sor – rotatable stern thruster, α_{dc} – angle of bow thruster rotation, α_{rc} – angle of stern thruster rotation.

Therefore, the real sailing training ship model is equipped with five thrusters – the matrix has five columns, wherein each of them correspondents to the forces derived from a particular propeller.

On the basis of a series of performed field tests, it was noted that when the longitudinal force (τ_x) determined by the controller takes a value greater than 80 N it is appropriate (in case of a sailing model) to use the main engine propeller in order to accelerate the vessel faster, which is equivalent to a faster growth of ships real force τ_x. In the case where value of the longitudinal force determined by the controller exceeds 140 N – it is not appropriate to use other thrusters except the main engine propeller. In a case where in the matrix $\mathbf{A}_{al}$ describing thrust allocation to individual thrusters, instead of momentary values of forces and moments in the individual actuators there will be zeros, as shown in equation:

$$\mathbf{A}_{al} = \begin{bmatrix} x_{ng} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{4}$$

The pseudo-inverse matrix takes the form given by equation:

$$\mathbf{A}_{al}^{g} = \begin{bmatrix} 1/x_{ng} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{5}$$

Which in the case of command Λ_{ng} calculation, that illustrates the main engine propeller speed, will lead to the relation given by formula (6). In the above mentioned case, in connection with operation of only the main engine, no other commands are determined.

$$\Lambda_{ng} = \frac{1}{x_{ng}}\tau_x \tag{6}$$

Assumption (6) implies, that the required value of main engine propeller revolutions is inversely proportional to the longitudinal force generated by this thruster and proportional to the value of the calculated longitudinal force τ_x. Because of that, the same longitudinal force determined in the control block, that would imply the increase of main engine propeller revolutions in order to reduce the longitudinal forces originating from this thruster. That is a false assumption. Previously used thrust allocation system for Blue Lady tanker [7] in terms of non significant longitudinal forces (which do not exceed 140 N) operated properly. Unfortunately, this solution applied to larger values of axial force does not give any opportunity for its usage, which is shown in figure 6.

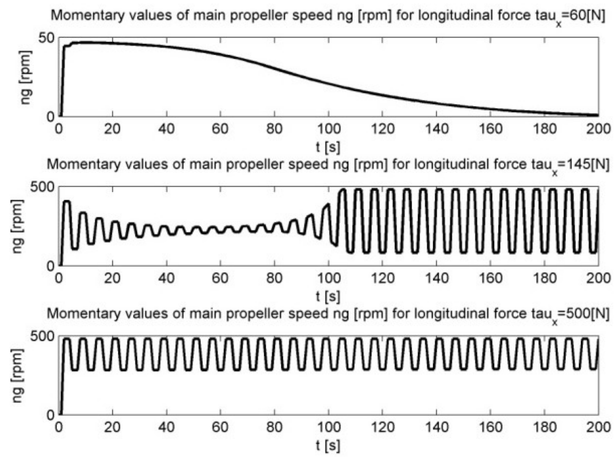

Fig. 6. Momentary values of main propeller speed *ng* [rpm] for longitudinal force τau$_x$ = 60 N, 145 N and 500 N

Analyzing figure 6, it is evident that for a small longitudinal force of 60 N – the main engine is used only in the first phase of ships acceleration and then propellers speed decreases to zero. For medium (145 N) and large (500 N) longitudinal forces, thrust allocation system working on the basis of the pseudo-inverse Moore-Penrose matrix is not applicable. There is a clearly visible appearance of oscillations, which are a direct result of the conversion illustrated by mathematical relation (3). Based on the conducted research it was noted, that this thrust allocation system can't be applied when it is necessary to accelerate the real sailing ship model to velocities exceeding 0.7 m/s (slow forward). Which corresponds to the need of producing a longitudinal force greater than 140 N.

Therefore, it was decided to designate the function of several variables that describe the dependence of main engine propeller revolutions depending on their momentary value (ng), longitudinal velocity (u) and longitudinal force (τ_x) as: $\Lambda_{ng} = f(ng, u, \tau_x)$. This relation was determined on the basis of non-linear mathematical model of the VLCC Blue Lady tanker [8]. On the basis of longitudinal velocity in the steady state (for a fixed set point of main engine propeller revolutions) force generated by the main engine propeller was read. Taking advantage of the possibility of approximation of the tabulated data by any polynomial in Matlab software, dependences were determined, which for the longitudinal force in the range are:

- $\tau_x \in \langle 80;250)$ is described by equation:

$$\Lambda_{ng} = -0.0022u \cdot ng^2 - 4.02 \cdot 10^{-4} \tau_x \cdot ng^2 + \\ + 0.0021 \tau_x \cdot ng \cdot u - 4.45 u^2 + 5.22 u + \\ + 0.0174 \tau_x + 0.1095 \tag{7}$$

- $\tau_x \in \langle 250;600\rangle$ is described by equation:

$$\Lambda_{ng} = -0.0614u \cdot ng^2 + 1.6 \cdot 10^{-4} \tau_x \cdot ng^2 + \\ - 5.2 \cdot 10^{-4} \tau_x \cdot ng \cdot u + 3.9221u + \\ + 0.009 \tau_x + 0.4674 \tag{8}$$

where:

- Λ_{ng} – given main engine propeller revolutions;
- u – momentary longitudinal speed;
- ng – momentary main engine propeller revolutions;
- τ_x – momentary longitudinal force produced by the action of the main engine.

When creating a relation that describes the value of given main engine propeller revolutions depending on the momentary longitudinal speed, main engine propeller revolutions and given longitudinal force produced by the action of the main engine, boundary conditions should be defined for which the relation is true and is fulfilling its task. Theoretically, the main engine propeller should be actuated only in case of calculation of a pure longitudinal force in the controller block. Transversal force and yaw moment should be equal to zero. In practical application the mentioned above (ideal) situation never occurs. Each multivariable controller working on the basis of a nonlinear model of a real floating ship (in case of the analyzed power distribution system – the VLCC Blue Lady tanker) will result in the calculation of the residual value of lateral force and torque. It is connected to the physical properties of real thrusters and vessel. For this reason, based on computer simulations and the analysis of their results limit values for which described above dependences are considered to be true, were chosen: momentary longitudinal ship

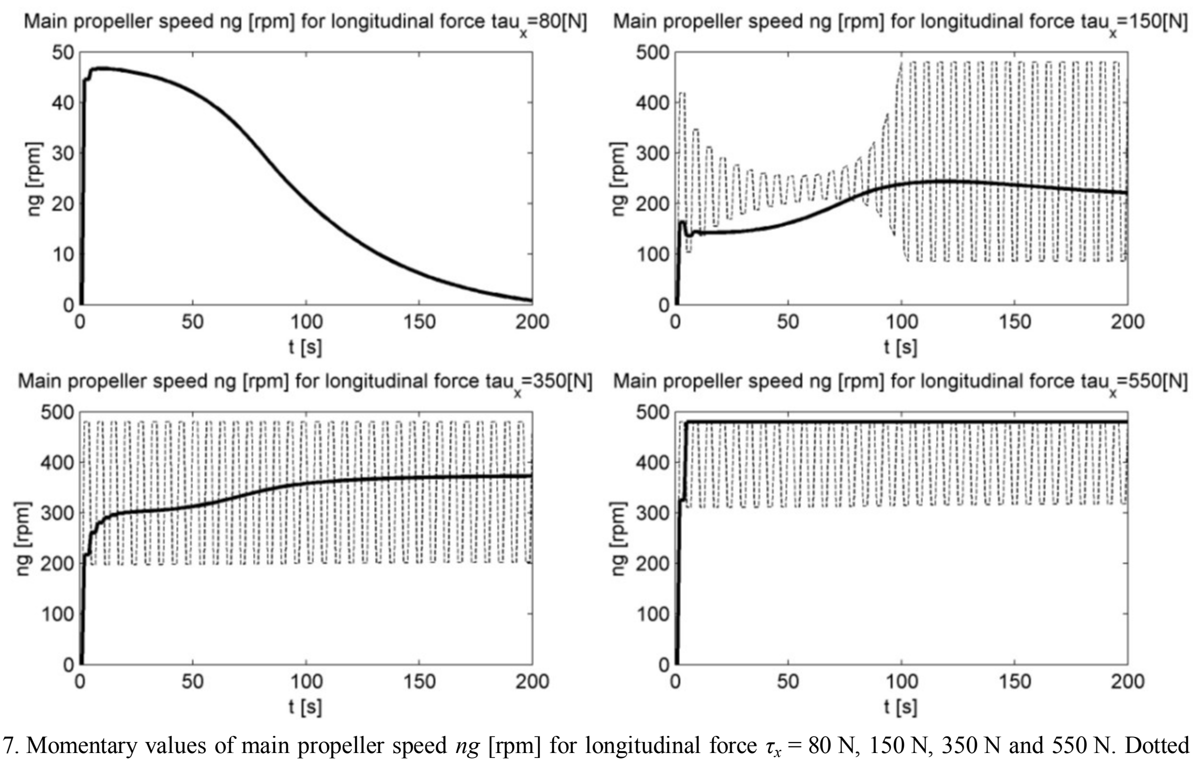

Fig. 7. Momentary values of main propeller speed ng [rpm] for longitudinal force τ_x = 80 N, 150 N, 350 N and 550 N. Dotted lines show the set points of main propeller operation with the system based only on the pseudo-inverse allocation matrix, and the continuous line, for the system using set point selection based on formulas (7) and (8)

velocities greater than or equal to 0 m/s, module of momentary value of the transversal force less than or equal to 15 N and module of momentary value of the torque less than or equal to 25 Nm.

Figure 7 illustrates a comparison of the effectiveness of two thrust allocation systems. It is clear that the modification of operation of a power distribution system for VLCC Blue Lady ships thrusters brought the desired result. Oscillations have been eliminated and the settings of main engine propeller are determined in a continuous manner, without explicit strokes, which are not desired in a real ships control system, because they may cause faster wear of the actuators. Performed modification allows the use of thrust allocation system in all conditions, for the full range of speeds that the training tanker model can achieve.

Results of simulations with verified thrust allocation system

In the simulation tests performed on the system shown schematically in figure 1 a multivariable controller designed on the basis of LMI (*Linear Matrix Inequality*) method was used [9]. For comparison two methods of thrust allocation were used. One of them is not taking into account the inclusion of main engine propeller for large values of determined longitudinal forces (called "old method") and the second one (called "proposed method") as described in Section *Thrust allocation system* of this article. The results of simulations carried out are shown in figures 8–14.

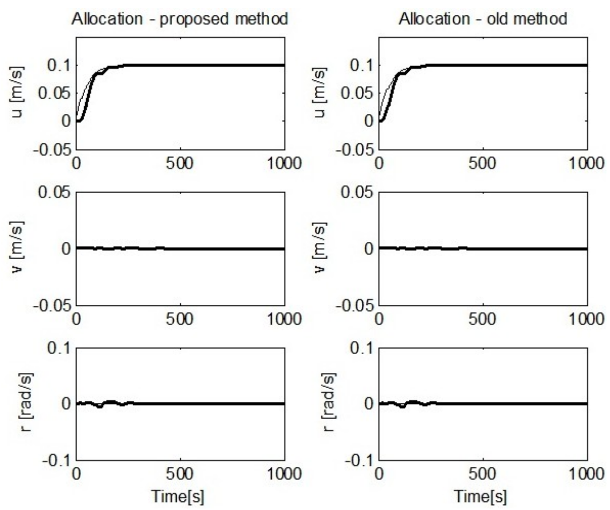

Fig. 8. Comparison of momentary values of longitudinal (u), lateral (v) and rotational (r) speeds, for a given value of longitudinal speed $u = 0.1$ m/s and two methods of power distribution between thrusters. Thick line – controlled value, thin line – set point value

As it can be seen at small values of longitudinal velocity, i.e. less than 0.1 m/s the usage of main engine propeller is not necessary. The work of other thrusters mounted on board is sufficient. This occurs because the desired value of longitudinal force developed by the regulator amounts in the steady state (this means the ship is moving at a constant speed) to 50 N. This is also presented in figure 10, showing individual working propellers. Main engine propeller, with the use of two algorithms of power distribution among all thrusters, is working in the same way. On the first and second graph values of main engine propeller revolutions designated as *ng* are equal when treated as a function of time. Namely, for both methods rotational speed of the propeller is about 80 rpm and the main engine is activated only in the acceleration phase of the ships motion, this is from 10 to 80 s of the simulation test.

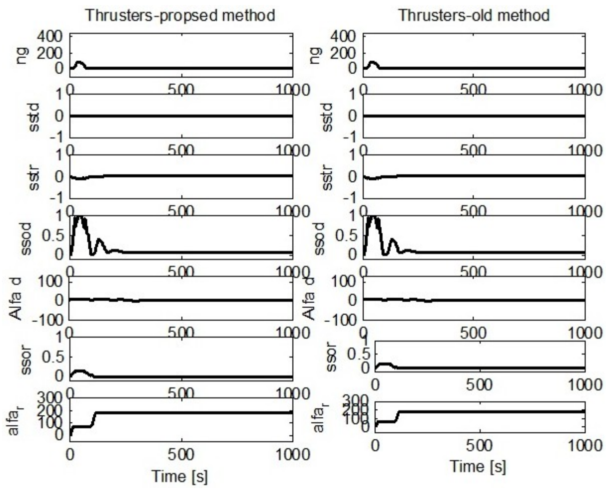

Fig. 9. Values of calculated command signals of individual thrusters with a given value of longitudinal speed $u = 0.1$ m/s and two methods of power distribution between thrusters

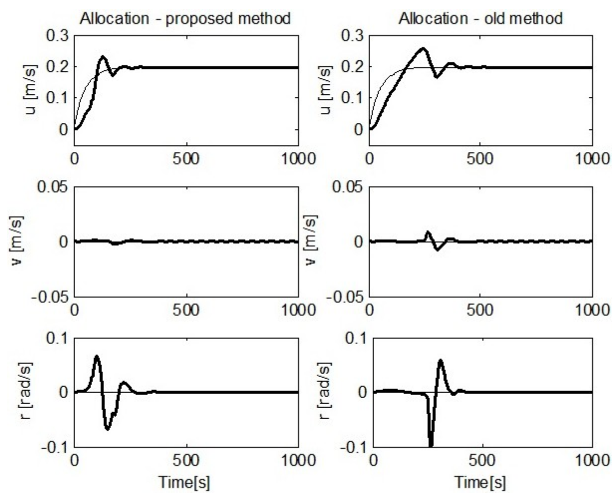

Fig. 10. Comparison of momentary values of longitudinal (u), lateral (v) and rotational (r) speeds, for a given value of longitudinal speed $u = 0.2$ m/s and two methods of power distribution between thrusters. Thick line – controlled value, thin line – set point value

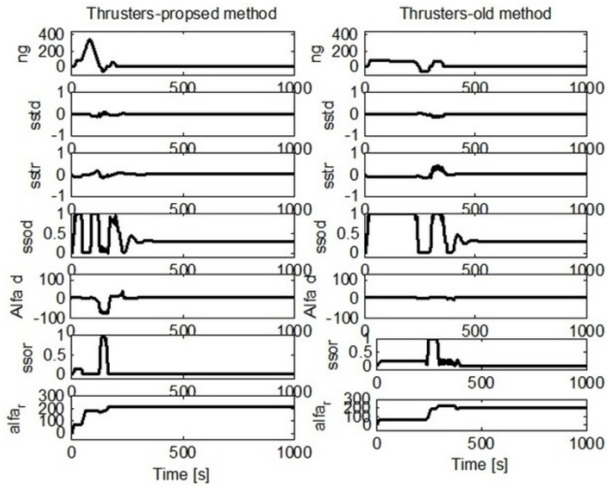

Fig. 11. Values of calculated command signals of individual thrusters with a given value of longitudinal speed $u = 0.2$ m/s and two methods of power distribution between thrusters

In figure 10 the difference in determination of controlled longitudinal speed against the set point value, i.e. 0.2 m/s can be seen. Settling time of regulated longitudinal velocity taking into account the conditions used in "proposed method" is about 380 s and when "old method" is used – it reaches 420 s. Also when the "old method" thrust allocation algorithm is used ships rate of turn exceeds –0.1 rad/s for simulation time of about 300 s. Additionally with the "old method" strokes in transverse speed occur between 200 and 400 s. In figure 11 the operation of all thrusters located on Blue Lady tanker model is shown. In case of the "proposed method" value of main engine propeller revolutions is increased to 400 rpm in the first 100 s of the motion, where in the "old method" this value does not exceed 100 rpm. It is clear that the dynamics of control value is much better than when thrust allocation is calculated with the "old method". The proposed thrust allocation algorithm allows quick ship acceleration to desired speed. It uses the main engine propeller and rotatable bow thruster as main actuators.

Test runs presented in figure 12 show significant difference in regulation time during settling of set point value of longitudinal speed up to 0.3 m/s. The value of settling time for "proposed method" algorithm is much lower and reaches about 450 s, compared to the "old method" where the settling time is more than 800 s. In this case, when observing the angular velocity (r), the advantage of the "old method" can be seen, for which in the first phase of motion – acceleration does not show oscillations. The work of individual propellers (Fig. 13) perfectly highlights the differences between those two methods of thrust allocation. It can be seen that a fast rise of main engine propeller revolutions, as shown in the figure 13 on the first chart to the left, called *ng*, in about the 50th and 300th second, increases controller dynamics. It can be compared with regulation time of the controller working with the "old method", where main engine propeller works constantly, but the revolutions have small values, i.e. about 50 rpm, which can be seen in the first graph to the right called *ng* in figure 13.

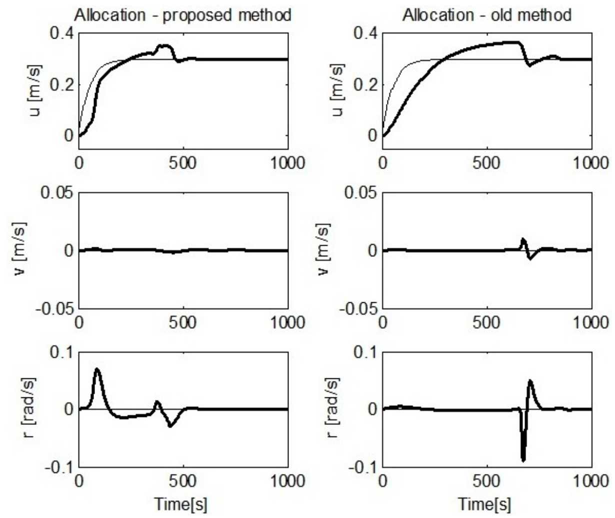

Fig. 12. Comparison of momentary values of longitudinal (u), lateral (v) and rotational (r) speeds, for a given value of longitudinal speed $u = 0.3$ m/s and two methods of power distribution between thrusters. Thick line – controlled value, thin line – set point value

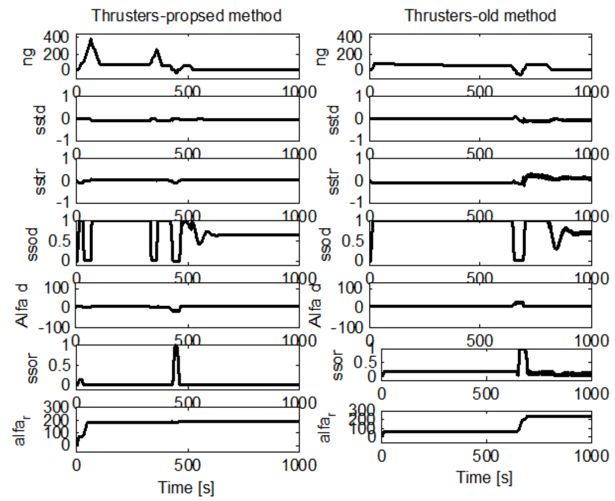

Fig. 13. Values of calculated command signals of individual thrusters with a given value of longitudinal speed $u = 0.3$ m/s and two methods of power distribution between thrusters

The results of computer simulations shown above illustrate the main differences in propulsion system operation when two methods of thrust allocation are applied. For a reference longitudinal speed value $u = 0.3$ m/s the settling time of the manipulated variable when using "new method" is about 430 s, while with the "old method" it exceeds

800 s. Therefore, when applying this solution, settling time can be reduced by more than 45%.

Conclusions

Thrust allocation system is an important element used in the process of ships automatic control. Adequate synthesis of the power distribution system greatly influences the quality of control, which has been confirmed by simulation studies. The results of computer simulations confirm, that application of the condition of main propeller starting when the reference longitudinal speed is greater or equal to 0.2 m/s causes the improvement of working conditions, including obtaining better dynamics of the ships model. This solution proves that it is more efficient to activate the main drive at longitudinal speed above 0.2 m/s than to use only rotatable thrusters of Blue Lady training model in the steering process.

When designing a thrust allocation system, special attention should be paid to special cases, which include for example the use of only one of many available propellers. Correctness of restrictions actually occurring in the system for individual thrusters and the need to cover full ships speed range are worth paying attention to as well.

In the presented study it was demonstrated that the introduced modification of main propeller revolutions calculation has a significant impact on control time and the disappearance of main engine revolution oscillations. It is important because in a real system actuator oscillations lead to its faster wear and the possibility of more frequent failure occurrence, which is associated with the increase of operational costs and should be avoided. Short settling time, while avoiding a large overshoot, is a desirable feature in all automatic control systems and is also a crucial element when talking about the quality of control. Therefore, settling time reduction is a desirable feature, which has been achieved by the creation of a new thrust allocation algorithm.

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