



## USING THE ROTATION CENTER AND PIVOT POINT TO OPTIMIZE VESSEL'S MANEUVER

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**Introduction.** Optimization of the vessel's maneuver is associated with the need to reduce the maneuvering space. This is especially true for all sorts of narrowness and ports. The size of vessels grows much faster than the size of ports, which causes more and more difficulties when maneuvering vessels in confined water areas. More accurate knowledge of the behavior of the vessel is required to minimize maneuvering space. By now, three directions of movement optimization have been identified.

The first direction is associated with a more accurate determination and taking into account the position of the vessel's rotation center in the control of the rotational motion. The knowledge about rotation center position was constantly changing. Initially, it was assumed that the vessel rotates around the gravity center. However, this is true for objects operating in not tight environment (aircraft, rockets, spacecraft). The vessel operates in the aquatic environment, the density of which is many times greater than the density of air. For this reason, water has a more significant effect on the behavior of the vessel, including the position of the Pivot Point. In further studies, for example [1] – [6], it is shown that for vessels the rotation center coincides with the point of application of the resultant lateral hydrodynamic force. Some authors called this rotation center as Pivot Point, although later another point was called as Pivot Point. The authors of this article believe that inaccuracies were made in determining the position of the rotation center, which will be discussed in the section of Research results.

The second direction is associated with the use of the Pivot Point in control. More than 85% of all vessels have a traditional stern rudder control scheme. When the stern rudder is deflected, a torque and a lateral force occur simultaneously, which leads to simultaneous rotational and lateral movement of the vessel. Such complex movement is difficult for the navigator to evaluate and make the right decision, which can lead to serious consequences. In this regard, in a number of works, control methods are considered, when it is recommended to replace such complex movement of the vessel with one rotational movement around a point called the Pivot Point. The position of this point is determined from the equation

$$R = -\frac{V_y}{\omega_z}, \quad (1)$$

where  $V_y$  is the lateral speed of the vessel,  $\omega_z$  is the angular rate of the vessel,  $R$  is the position of the Pivot Point relative to the gravity center of the vessel [7] – [9]. According to the authors of this article, formula (1) determines the position of the Pivot Point relative to the rotation center, but not in any way relative to the gravity center of the vessel, since the vessel rotates at angular rate  $\omega_z$  relative to the rotation center. In



article [10] an experimental determination of the Pivot Point position was also proposed. Articles [7] – [10] also did not show how to use the pivot point position, obtained in equation (1), for practical maneuvering, that is, no further relationship was shown between the Pivot Point position and controls (stern rudder deflection and thruster deflection to make such rotation).

The third direction is associated with the use of mathematical methods for optimal control of the vessel's movement in automatic mode. This direction in relation to the control of the vessel's movement around the Pivot Point has not been found by the authors in open sources.

The relevance of research. As follows from the above, the optimization of the vessel's movement to reduce the space, required for maneuver, is an urgent scientific and technical problem.

Formulation of the problem. It is required to synthesize control algorithms that make it possible to reduce the space required for the vessel's maneuver by optimizing the rotational movement: more accurately determining the position of the rotation center, the Pivot Point, using them to form controls for the vessel's actuators, and forming the time optimal controls.

**Results of researches.** Determining and taking into account the position of the rotation center in vessel control. The authors of this article believe that, unlike [1] - [6], the position of the vessel's rotation center is determined not only by the hydrodynamic characteristics of the ship, but also by its mass inertial characteristics, therefore, the rotation center should be somewhere between the vessel's gravity center and the center of the resultant lateral hydrodynamic force application. To determine the position of the rotation center, the authors made the following assumption: the applied torque relative to the rotation center should have the greatest efficiency, that is, the condition should be met

$$\varepsilon(x_0) = \frac{M_{zu}(x_0) - M_{zg}(x_0)}{I_z(x_0)} \rightarrow \max \quad (2)$$

where  $\varepsilon(x_0)$  is angular acceleration about the rotation center  $x_0$ ,

$M_{zu}(x_0)$  is applied moment relative to the rotation center  $x_0$ ,

$M_{zg}(x_0)$  is moment of hydrodynamic resistance relative to the rotation center  $x_0$ ,

$I_z(x_0)$  is moment of inertia of the vessel about the rotation center  $x_0$ ,

$x_0$  is coordinate of the vessel's rotation center relative to the gravity center.

From equation (2) the dependence of the rotation center position on the speed of the vessel is obtained

$$x_0 = \frac{L}{2} \left( 1 - \frac{V_{\max}}{V + V_{\max}} \right), \quad (3)$$

where  $L$  is the vessel length,  $V$  is the vessel speed,  $V_{\max}$  is the maximum vessel speed.



Formation of rotational motion controls around the Pivot Point. The system of equations that determines the lateral and rotational motion of the vessel is as follows

$$\begin{aligned}
 m \frac{dV_y}{dt} &= \frac{dF_y}{d\delta_r} \delta_r + \frac{dF_y}{d\delta_T} \delta_T - \frac{dF_y}{dV_y} V_y, \\
 I_z \frac{d\omega_z}{dt} &= -\frac{dF_y}{d\delta_r} l_r \delta_r + \frac{dF_y}{d\delta_T} l_T \delta_T - \frac{dM_z}{d\omega_z} \omega_z,
 \end{aligned}
 \tag{4}$$

where  $\frac{dF_y}{dV_y}, \frac{dM_z}{d\omega_z}$  is hydrodynamic characteristics of the vessel,

$\frac{dF_y}{d\delta_r}, \frac{dF_y}{d\delta_T}$  is control characteristics,

$\delta_r, \delta_T$  are the angles of rudder deflection and the thruster deflection, respectively,

$l_r, l_T$  are the arms from rudder and thruster to center of rotation, respectively.

For steady motion  $V_y = const, \omega_z = const$ , system (4) can be written as

$$\begin{aligned}
 V_y &= \frac{dF_y dV_y}{d\delta_r dF_y} \delta_r + \frac{dF_y dV_y}{d\delta_T dF_y} \delta_T, \\
 \omega_z &= -\frac{dF_y d\omega_z}{d\delta_r dM_z} l_1 \delta_r + \frac{dF_y d\omega_z}{d\delta_T dM_z} l_2 \delta_T
 \end{aligned}
 \tag{5}$$

From equations (1), (5) determine the dependence  $\delta_r = k_{ru} \delta_T$  between the angle of rudder deflection and the angle of thruster deflection for the implementation of movement around a given Pivot Point

$$\delta_r = -\frac{\frac{dF_y}{d\delta_T} \left( \frac{dV_y}{dF_y} + R^* \frac{d\omega_z}{dM_z} l_T \right)}{\frac{dF_y}{d\delta_r} \left( \frac{dV_y}{dF_y} - R^* \frac{d\omega_z}{dM_z} l_r \right)} \delta_T
 \tag{6}$$

Fig. 1 shows a dependence of the control distribution coefficient  $k_{ru}$  on the position of the Pivot Point  $R^*$  for one of the offshore vessels OSV3.

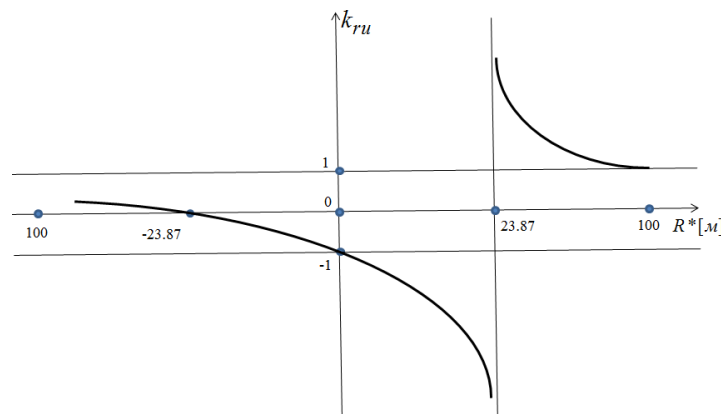


Figure 1. Dependence of the control distribution coefficient on the position of the Pivot Point



Fig. 2 shows the areas of admissible controls that determine the movements around a given Pivot Point, as well as all other possible variants of movement.

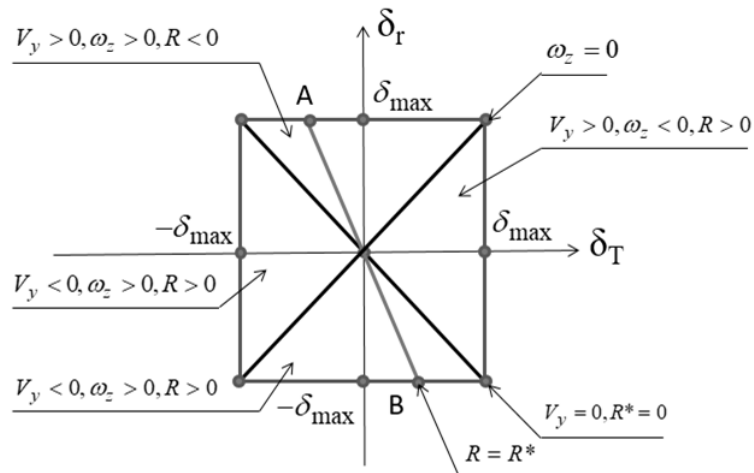


Figure 2. Areas of admissible controls

Optimal controls. Points A and B in Fig. 4 correspond to the time optimal control of the vessel's rotation around the Pivot Point  $R^*$ , since according to the Pontryagin maximum principle for systems, linear on control, optimal control lie on the admissible controls area boundary.

Conclusions. The following tasks were solved in the work:

- control algorithms were synthesized to reduce the space, required for the vessel's maneuver by optimizing rotational motion;
- the formula for determining the position of the center of rotation depending on the speed of the vessel is obtained;
- the formula for determining the position of the Pivot Point was refined;
- a graph of the control distribution coefficient dependence on the position of the Pivot Point is built;
- control areas are obtained that ensure the rotation of the vessel around the Pivot Point, other movements of the vessel with given parameters;
- time optimal control of the vessel's rotation around the Pivot Point is obtained.

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