WHAT IS THE PIVOT POINT AND HOW TO USE IT TO CONTROL THE VESSEL

Zinchenko S.M., Tovstokoryi O.M.
Kherson State Maritime Academy
(Ukraine)

Introduction. Recently, the number and size of ships has increased significantly. The size of ports increases much slower than the growth in the number and size of ships, which requires a more accurate understanding of the behavior of the vessel during maneuvering. So, it was previously believed that rotation point of the vessel coincided with the center of gravity. However, numerous practical experience has shown that this is not so. Inaccurate knowledge of the position of the rotation point leads to a significant increase in the maneuvering area, which is not desirable in cramped waters. The research of the position of the pivot point of the vessel has been the subject of many works, some of which [1-14] are given in the list of references to this article. In articles [3–7, 14], the authors call the rotation point of the vessel as pivot point and determine its position as the point of application of the resultant transverse hydrodynamic forces. In works [8-13], the pivot point is considered as a conditional point at which the drift angle is zero. The position of this point is determined by the values of the lateral speed component of the vessel and the angular rate of vessel around the center of gravity. This allows to consider two ship movements - lateral and rotational as one movement around the pivot point, which is much more optimal. In works [8, 11] were considered various practical cases, when taking into account the position of the pivot point can optimize control.

Relevance of research. Unfortunately, determining the position of the pivot point relative to the center of gravity, as suggested in works [8, 11], is not entirely correct, since the vessel does not rotate relative to the center of gravity, but relative to the center of rotation, as was shown in the works [3–7, 14], whose position is determined as the point of application of the resultant transverse hydrodynamic forces. In addition, in works [8, 11] were given only recommendations on the use of the position of the pivot point in control, but not given a specific methods and algorithms for determining the rotation control of a vessel around a pivot point. Therefore, the solution of the problem of determining the rotation center position, pivot point position, as well as their use for the formation of rotation control is an urgent scientific and technical problem.

Problem statement. Is given a mathematical model of the control object in the form of a linear differential equations of lateral and angular motion of the vessel with controls δ_1, δ_2.

$$m\frac{dV_y}{dt} = \frac{dF_y}{d\delta_1}\delta_1 + \frac{dF_y}{d\delta_2}\delta_2 - \frac{dF_y}{dV_y}V_y,$$

$$I_z\frac{d\omega_z}{dt} = -\frac{dF_y}{d\delta_1}l_1\delta_1 + \frac{dF_y}{d\delta_2}l_2\delta_2 - \frac{dM_z}{d\omega_z}\omega_z, \qquad (1)$$

It is required to find controls δ_1, δ_2, that ensure the rotation of the vessel around a given pivot point, including optimal.

Research results. Rotation center. In [14], it was noted that the center of lateral resistance of the vessel is located between the gravity center of the vessel and the center of its underwater part. Indeed, in the absence of hydrodynamic resistance, the rotation center of the vessel will coincide with the gravity center, and in the absence of inertia moments, the rotation center of the vessel will coincide with the center of lateral hydrodynamic resistance. If both factors are present, the rotation center of the vessel will be between the center of gravity and the center of lateral hydrodynamic resistance. Moreover, the authors of this article believe that the rotation center of the vessel located at the point relative to which it is easiest to rotate the vessel, that is, at the point relative to which the vessel will have the greatest angular acceleration from the applied torque M.

$$\frac{d\omega_z}{dt} = \frac{M - \Delta F(l_0 - \Delta x)}{I_z + m\Delta x^2} \to \max$$
,

After transformations, determine the displacement Δx of the rotation center relative to the center of gravity

$$\Delta x = \frac{L}{2}(1 - \frac{V_{\max}}{V + V_{\max}}). \quad (2)$$

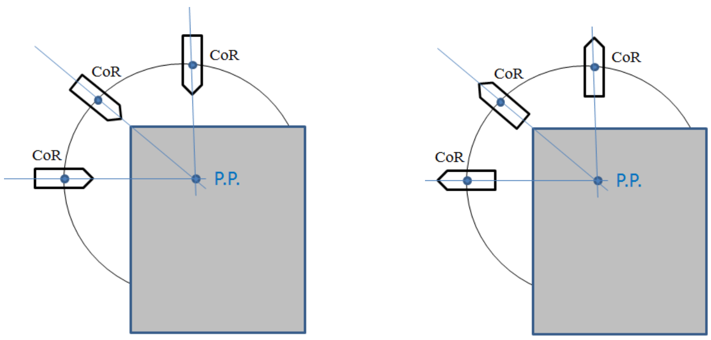
As can be seen from formula (2), the center of rotation is shifted slowly relative to the center of gravity of the vessel along a hyperbole, depending on the speed of the vessel. The limit position of the rotation center with an unlimited increase in speed is $\Delta x = \frac{L}{2}$.

Pivot point. As noted in works [8–13], the pivot point is a conditional point relative to which two movements — lateral and rotational around the rotation center look like one rotational around the pivot point. A feature of this point is the absence in it of the total lateral speed from lateral and rotational movements $V_y + \omega_z R = 0$,

$$R = -\frac{V_y}{\omega_z}. \quad (3)$$

As follows from equation (3), a necessary and sufficient condition for the existence of a pivot point is the presence of a lateral component V_y of linear speed and angular rate ω_z relative to the rotation center. From formula (3) it follows that position R of rotation center is very mobile and can change very quickly in the range $-\infty \le R \le +\infty$ when the angular rate fluctuates around zero. Thus, as follows from the above, the rotation centre, the pivot point and the gravity centre of the vessel are three different points which don't always coincide with each other.

Turning control. Figure 1 shows one of the practical applications of the pivot point when maneuvering a vessel around a hazard for positive and negative values of the pivot point.



Fig, 1 - Turn around a pivot point

From the system (1), for the steady state of motion, determine the dependence of the lateral speed and angular rate of the vessel on the controls δ_1, δ_2.

$$V_y = \frac{dF_y \, dV_y}{d\delta \, dF_y}(\delta_1 + \delta_2),$$

$$\omega_z = \frac{dF_y \, d\omega_z}{d\delta \, dM_z}(-l_1\delta_1 + l_2\delta_2).$$

or, taking into account formula (3)

$$\delta_1 = -\frac{(\frac{dV_y}{dF_y} + R * \frac{d\omega_z}{dM_z} l_2)}{(\frac{dV_y}{dF_y} - R * \frac{d\omega_z}{dM_z} l_1)} \delta_2 \quad (4)$$

Fig. 2 shows the areas of admissible controls in which the required rotations are realized.

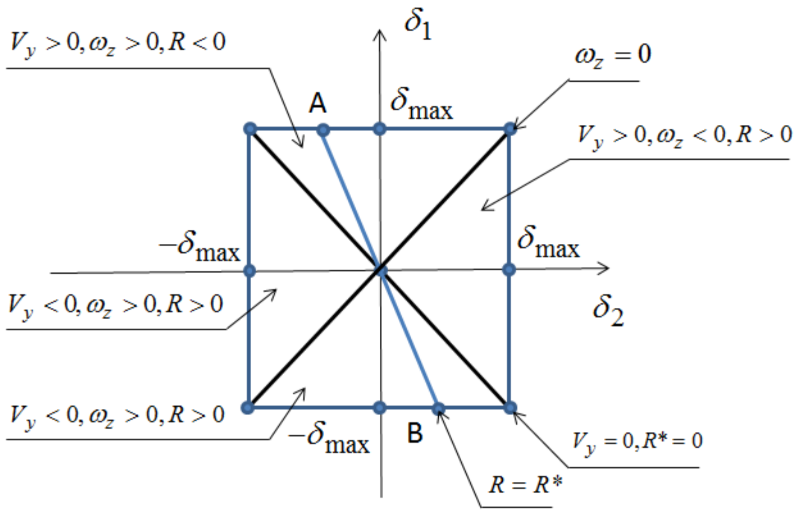


Fig. 2 – Areas $R = R^*, V_y = 0, \omega_z = 0$

Optimal controls. As follows from Fig. 2, the required rotations of the vessel can be implemented in many ways. Thus, the rotation of the vessel around a given position $R = R^*$ of the pivot point can be implemented by a variety of controls located on the segment AB. Optimal controls, according to the maximum principle, will be located at points A or B. In point A $\delta_1 = \delta_{max}$ and δ_2 is determined from equation (4), in point B $\delta_1 = -\delta_{max}$ and δ_2 is determined from equation (4).

The performance check of the proposed method and algorithms was carried out on a Navi Trainer 5000 simulator .The point for which a optimal maneuver was calculated is located at the extremity of one of the breakwaters in the Bosphorus Strait. Using the formula (4), there were calculated the positions of the thrusters for a speed-optimal turn around a given pivot point and the thrusters were set to a pre -calculated position. As the simulation results showed, the pre-calculated controls ensured the rotation of the vessel around a given position of the pivot point

Conclusion.

- it is shown that the rotation centre, the pivot point and the gravity centre of the vessel are three different points, which, in the general case, do not coincide with each other.
- rotation center of the vessel located at the point relative to which it is easiest to rotate the vessel, that is, at the point relative to which the vessel will have the greatest angular acceleration from the applied torque $\Delta x = \frac{L}{2}(1 - \frac{V_{max}}{\Delta V + V_{max}})$. Rotation center is shifted slowly relative to the gravity center of the vessel along a hyperbole, depending on the speed of the vessel. The limit position of the rotation center with an unlimited increase in speed is $\Delta x = \frac{L}{2}$;
- a necessary and sufficient condition for the existence of a pivot point is the presence of a lateral component V_y of linear speed and angular rate ω_z relative to the rotation center. Position R of rotation center is very mobile and can change very quickly in the range $-\infty \le R \le +\infty$ when the angular rate fluctuates around zero.
- there were constructed the areas of admissible controls in which the required rotations are realized;
- it was obtained optimal motion control around the pivot point;
- the correctness of the method and algorithms were verified by mathematical modeling on a navigation simulator Navi Trainer 5000.

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