

## The Choice of the Maneuver of the Vessel's Passing Considering the Coordination's System of the Interactive Vessels and Their Dynamic Characteristics

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**ABSTRACT:** The maneuver of the altering course of the vessel is a more preferable to avoid a collision. Due to that the calculation of the parameters of the avoidance maneuver should be done considering the dynamic characteristics of the vessel in maneuvering. The paper analyzes the dynamic models of the vessel rotation motion in order to select more appropriate one for the calculation of avoidance maneuver of the vessel applying the altering of the course.

### 1 INTRODUCTION

The paper focuses on the situation of dangerous approach of the ships that requires a maneuver passing, the nature of which determines the system of coordination of their interaction and realizes the area of mutual responsibilities. For the prevention of each of the vessels collisions, the coordination system prescribes a specific type of behavior (the maneuvering or saving of the parameters of motion). It helps to operate the ship flexible strategy passing, which contains a priority maneuver, taking into account the prescribed type of behavior of interacting ships, and reserves the maneuver for the case of ignoring the partner prescribed duties. To avoid collisions, the maneuver of changing the ship's course is preferable. The paper stresses upon the calculation of the altering course maneuver parameters, considering the dynamic characteristics of the maneuvering of the vessel. It is also given the dynamic model of rotational motion of the vessel, which is the most suitable for calculating the parameters of the altering course maneuvers of the vessels.

### 2 MAIN PART

#### 2.1 Setting up the task

Let's see the situation dangerous approach of operating the vessel ( $c_1$ ) to ( $c_2$ ) when near the proposed passing area is another ship ( $c_3$ ). In this case, the matrix of situational disturbance is  $W = \{\omega_{ij}\}$  (Pyatakov 2015). See Equation 1 below:

$$W = \begin{pmatrix} 0 & \omega_{12} & \omega_{13} \\ \omega_{21} & 0 & \omega_{23} \\ \omega_{31} & \omega_{32} & 0 \end{pmatrix} \quad (1)$$

For the case (1) the values of the situational disturbances  $\omega_{12}$  and  $\omega_{21}$  are not equal to zero. Therefore, the vessels  $c_1$  and  $c_2$  interact. Binary coordinator  $Coor(2)$ , implemented in COLREGs-72, determines the nature of such interaction. The vessels decide to make a coordinated maneuver of passing, compensating situational disturbance, i.e. ensuring the circulation of values, situational disturbances  $\omega_{12}$  and  $\omega_{21}$  zero. The strategy of passing, formed by

operating vessel, depends on the initial values for the situational disturbances  $\omega_{13} = \omega_{31}$  and  $\omega_{23} = \omega_{32}$ .

## 2.2 The case of interacting

In the case  $\omega_{13} = 0$  and  $\omega_{23} = 0$  the presence of the vessel  $c_3$  does not cause the appearance of its interaction with operating vessel and target. In this situation  $G^{(1)}$  there is only the interaction  $B_{z12}$  between the operating vessel  $c_1$  and a dangerous target  $c_2$  and the coordinator  $Coor^{(2)}$  that is based on the relative positions of the vessels  $S_{12}$  and their statuses  $St_1$  and  $St_2$  directs interactive vessels coordinating signals  $\gamma_{12}$  and  $\gamma_{21}$  (Pyatakov 2015; Burmaka 2016).

These signals determine their behavior in the process of the passing, each of them prescribing reciprocal duties, allowing the ships to make choice of strategies passing. While one of the vessels retains its motion parameters, the second one executes a maneuver passing or both vessels perform coordinated maneuvers of the passing.

## 2.3 Choosing the maneuver

Therefore, operating ship  $C_1$  chooses a strategy of the passing  $D_1^{(h)}$ , grounding on the coordinating signal  $\gamma_{12}$  and realized area of mutual obligations. Moreover, if the coordinator instructs the operating vessel  $C_1$  to give way to the target  $c_2$  ( $\gamma_{12}^{(1)} = 1$ ), altering course maneuver  $D_1^{(1)}$  is selected by the strategy of passing  $D_1^{(1)}$ .

If  $\gamma_{12}^{(1)} = 0$  the operating vessel gets the instruction from the coordinator to maintain the motion parameters  $D_1^{(0)}$ . Then the ship follows the prescribed strategy  $D_1^{(0)}$  until the pointing time  $\tilde{t}$  when performing the maneuver  $\tilde{D}_1^{(t)}$  it should prevent a possible collision because of the inaction target  $c_2$ , which does not give a way  $D_2^{(0)}$ . In this situation  $G^{(1)}$ , strategy  $D_1^{(1)}$  is defined as follows (2):

$$D_1^{(1)} = \begin{cases} D_1^{(1)}, & \text{if } \gamma_{12}^{(1)} = 1; \\ D_1^{(0)}, & \text{if } \gamma_{12}^{(1)} = 0, D_2^{(1)}; \\ D_1^{(0)}, & \text{if } \gamma_{12}^{(1)} = 0, D_2^{(0)}, t \leq \tilde{t}; \\ \tilde{D}_1^{(\tilde{t})}, & \text{if } \gamma_{12}^{(1)} = 0, D_2^{(0)}, t > \tilde{t}. \end{cases} \quad (2)$$

## 2.4 The second case of cooperating

Let's see the situation  $G^{(2)}$  when  $\omega_{13} = 1$  and  $\omega_{23} = 0$ . In this case, in addition to the interaction  $B_{z12}$  between the ships  $c_1$  and  $c_2$  there is an interaction  $B_{z13}$  between the ships  $c_1$  and  $c_3$ . Consequently, the coordinator  $Coor^{(2)}$  generates coordination signals  $\gamma_{12}^{(2)}$ ,  $\gamma_{21}^{(2)}$ ,  $\gamma_{13}^{(2)}$  and  $\gamma_{31}^{(2)}$ . The signals  $\gamma_{12}^{(2)}$  and  $\gamma_{13}^{(2)}$  are addressed to the operating vessel by the coordinator. They can prescribe it one type of behavior ( $\gamma_{12}^{(2)} = 1$ ,  $\gamma_{13}^{(2)} = 1$  or another  $\gamma_{12}^{(2)} = 0$ ,  $\gamma_{13}^{(2)} = 0$ ), that means to maneuver or maintain a constant flow parameters, or

contradict each other ( $\gamma_{12}^{(2)} = 1$ ,  $\gamma_{13}^{(2)} = 0$  or  $\gamma_{12}^{(2)} = 0$ ,  $\gamma_{13}^{(2)} = 1$ ).

In the case of sequence coordination of signals  $\gamma_{12}^{(2)} = 1$  and  $\gamma_{13}^{(2)} = 1$ , the operating vessel must give way to vessels  $c_2$  and  $c_3$  by the passing maneuver  $D_1^{(2)}$  (1), which can be realized in one of two possible options: common for vessels  $c_2$  and  $c_3$  maneuver or two consecutive maneuvers for each of the vessels.

### 2.4.1 Strategy of cooperating the vessels in the second case

If the coordinating signals  $\gamma_{12}^{(2)} = 0$ ,  $\gamma_{13}^{(2)} = 0$  require from the operating vessel to maintain a constant flow parameters relative to both vessels  $c_2$  and  $c_3$  then the operating ship follows a constant course and speed  $D_1^{(2)}(0)$ , provided that the objectives  $c_2$  and  $c_3$  carry out altering course maneuvers  $D_2(1)$  and  $D_3(1)$ . If one of the target or both targets do not give way to the operating vessel, the latter follows a constant course and speed  $D_1^{(2)}(0)$  until the pointing time  $\tilde{t}$  after which the vessel  $C_1$  is forced to maneuver  $D_1^{(2)}(\tilde{t})$  to prevent a possible collision.

In the case when coordinating signals contradict each other ( $\gamma_{12}^{(2)} = 1$ ,  $\gamma_{13}^{(2)} = 0$  or  $\gamma_{12}^{(2)} = 0$ ,  $\gamma_{13}^{(2)} = 1$ ), operating vessel uses altering course passing in time zero  $D_1^{(2)}(\tilde{t}_0)$ , which is safe for ships  $c_2$  and  $c_3$ . In this situation  $G^{(2)}$ , strategy  $D_1^{(2)}$  is defined as follows (3):

$$D_1^{(2)} = \begin{cases} D_1^{(2)}(1), & \text{if } \gamma_{12}^{(2)} = 1, \gamma_{13}^{(2)} = 1; \\ D_1^{(2)}(0), & \text{if } \gamma_{12}^{(2)} = 0, \gamma_{13}^{(2)} = 0, D_2^{(1)}, D_3^{(1)}; \\ D_1^{(2)}(0), & \text{if } \gamma_{12}^{(2)} = 0, \gamma_{13}^{(2)} = 0, D_2^{(0)}, D_3^{(0)}, t \leq \tilde{t}; \\ \tilde{D}_1^{(2)}(\tilde{t}), & \text{if } \gamma_{12}^{(2)} = 0, \gamma_{13}^{(2)} = 0, D_2^{(0)}, D_3^{(0)}, t > \tilde{t}; \\ \bar{D}_1^{(2)}(t_0), & \text{if } \gamma_{12}^{(2)} = 0, \gamma_{13}^{(2)} = 1; \\ \bar{D}_1^{(2)}(t_0), & \text{if } \gamma_{12}^{(2)} = 1, \gamma_{13}^{(2)} = 0. \end{cases} \quad (3)$$

## 2.5 The third case of cooperating

Another situation  $G^{(3)}$  is characterized by situational disturbances  $\omega_{13} = 0$  and  $\omega_{23} = 1$ , thus in addition to the interactions  $B_{z12}$  there is an interaction  $B_{z23}$  between the ships  $c_2$  and  $c_3$ . In this situation, the coordinator formed a coordinating signals  $\gamma_{12}^{(3)}$ ,  $\gamma_{21}^{(3)}$ ,  $\gamma_{23}^{(3)}$  and  $\gamma_{32}^{(3)}$ .

If the signals of coordination  $\gamma_{12}^{(3)} = 1$ ,  $\gamma_{21}^{(3)} = 0$ ,  $\gamma_{23}^{(3)} = 1$  and  $\gamma_{32}^{(3)} = 0$  realized, the operating ship  $C_1$  should give a way to the ship  $c_2$  performing the maneuver  $D_1^{(3)}(1)$ , remembering that  $c_2$  performs the maneuver  $D_2^{(1)}$  with the ship  $c_3$ .

Similarly, a strategy of the passing of the operating vessel under the coordination of the signals  $\gamma_{12}^{(3)} = 1$ ,  $\gamma_{21}^{(3)} = 0$ ,  $\gamma_{23}^{(3)} = 0$  and  $\gamma_{32}^{(3)} = 1$  is formed. The maneuver  $D_3^{(1)}$  of the passing of the vessel  $c_3$  is taking into account.

### 2.5.1 Strategy of cooperating the vessels in the third case

In the case of signal coordination  $\gamma_{12}^{(3)} = 0$ ,  $\gamma_{21}^{(3)} = 1$ ,  $\gamma_{23}^{(3)} = 1$   $\gamma_{32}^{(3)} = 0$  and  $\gamma_{32}^{(3)} = 1$ , when the operating ship

should maintain its motion parameters, its strategy is to follow with constant course and speed  $D_1^{(3)}(0)$ , if the target  $c_2$  performs a maneuver passing  $D_2(1)$ .

A similar strategy  $D_1^{(3)}(0)$  is used in the implementation of signal coordination  $\gamma_{12}^{(3)} = 0$ ,  $\gamma_{21}^{(3)} = 1$ ,  $\gamma_{23}^{(3)} = 1$  and  $\gamma_{32}^{(3)} = 0$ . If, however, for both cases the target  $c_2$  in contrary to the requirements of the coordinator does not give a way to the operating vessel  $D_2(0)$  though it got the coordinating signals, the latter implement a strategy  $D_1^{(3)}(0)$  of point-in-time  $\tilde{t}$ , and then the operating ship  $C_1$  takes its own  $D_1^{(3)}(\tilde{t})$  maneuver of the passing. Thus, in a situation  $G^{(3)}$  the strategy  $D_1^{(3)}$  is calculated according to the Equation 4:

$$D_1^{(3)} = \begin{cases} D_1^{(3)}(1), & \text{if } \gamma_{12}^{(3)} = 1; \\ D_1^{(3)}(0), & \text{if } \gamma_{12}^{(3)} = 0, D_2(0); \\ D_1^{(3)}(0), & \text{if } \gamma_{12}^{(3)} = 0, D_2(0), t \leq \tilde{t}; \\ \tilde{D}_1^{(3)}(\tilde{t}), & \text{if } \gamma_{12}^{(3)} = 0, D_2(0), t > \tilde{t}. \end{cases} \quad (4)$$

## 2.6 Interaction case

The final situation  $G^{(4)}$  realizes under the situational disturbances  $\omega_{13} = 1$  and  $\omega_{23} = 1$  in which besides the interactions of  $Bz_{12}$  there may be also interactions  $Bz_{13}$  and  $Bz_{23}$  accordingly between vessels  $c_1$  and  $c_3$ , and between vessels  $c_2$  and  $c_3$ . In this situation, the coordinator forms coordinating signals  $\gamma_{12}^{(4)}$ ,  $\gamma_{21}^{(4)}$ ,  $\gamma_{13}^{(4)}$ ,  $\gamma_{31}^{(4)}$ ,  $\gamma_{23}^{(4)}$  and  $\gamma_{32}^{(4)}$ . Therefore, the operating behavior of the ship  $c_1$  in the first place is determined by the ratio of the coordination signals  $\gamma_{12}^{(4)}$  and  $\gamma_{13}^{(4)}$ . If these signals are agreed upon  $\gamma_{12}^{(4)} = 1$  and  $\gamma_{13}^{(4)} = 1$ , then the operating ship  $c_1$  should perform a passing maneuver  $D_1^{(4)}(1)$ , which can be common to ships  $c_2$  and  $c_3$  and consist of two consecutive maneuvers, and give way to vessels  $c_2$  and  $c_3$ .

### 2.6.1 Strategy for interaction in the fourth case

In the case of the coherent coordination of signals  $\gamma_{12}^{(4)} = 0$  and  $\gamma_{13}^{(4)} = 0$  if the ships  $c_2$  and  $c_3$  carry out altering course maneuvers  $D_2(1)$  and  $D_3(1)$  the operating vessel must maintain a constant flow parameters, implementing strategies  $D_1^{(4)}(0)$ . In the case when one of the targets does not give a way to the operating vessel, the latter follows a constant course and speed  $D_1^{(4)}(0)$  until the pointing time  $\tilde{t}$  after which vessel  $C_1$  performs the maneuver  $\tilde{D}_1^{(4)}(\tilde{t})$  to avoid of a possible collision.

In the case when coordinating signals contradict each other ( $\gamma_{12}^{(4)} = 1$ ,  $\gamma_{13}^{(4)} = 0$  or  $\gamma_{12}^{(4)} = 0$ ,  $\gamma_{13}^{(4)} = 1$ ), operating vessel is taking passing maneuver at a zero point of time  $\bar{D}_1^{(4)}(t_0)$ , which is safety for both  $c_2$  and  $c_3$  vessels. Thus, in a situation  $G^{(4)}$  strategy  $D_1^{(4)}$  is shown in Equation 5:

$$D_1^{(4)} = \begin{cases} D_1^{(4)}(1), & \text{если } \gamma_{12}^{(4)} = 1, \gamma_{13}^{(4)} = 1; \\ D_1^{(4)}(0), & \text{если } \gamma_{12}^{(4)} = 0, \gamma_{13}^{(4)} = 0, D_2(1), D_3(1); \\ D_1^{(4)}(0), & \text{если } \gamma_{12}^{(4)} = 0, \gamma_{13}^{(4)} = 0, D_2(0), D_3(0), t \leq \tilde{t}; \\ \tilde{D}_1^{(4)}(\tilde{t}), & \text{если } \gamma_{12}^{(4)} = 0, \gamma_{13}^{(4)} = 0, D_2(0), D_3(0), t > \tilde{t}; \\ \bar{D}_1^{(4)}(t_0), & \text{если } \gamma_{12}^{(4)} = 0, \gamma_{13}^{(4)} = 1; \\ \bar{D}_1^{(4)}(t_0), & \text{если } \gamma_{12}^{(4)} = 1, \gamma_{13}^{(4)} = 0. \end{cases} \quad (5)$$

## 2.7 General situations of vessels interaction

The situation  $G^{(i)}$  ( $i=1 \div 4$ ) provides for binary interaction of the vessels with the opposite coordinating signals when one of the ships should take an altering course passing, and the second ship must not change the parameters of its motion. The coordinator COLREG-72 mentions only one situation (Rule 14) when the standard interaction of the ships is in the simultaneous maneuvering of the vessel and operating target. In this situation, the operating ship chooses the maneuver of altering course to the starboard independently from the target and the third vessel behavior.

As COLREGs-72 points out, under the condition of sufficient water space more preferable maneuver of the passing is to change the ship's course. Therefore, after identifying situational disturbance the operating ship should realize the situation  $G^{(i)}$  and calculate the parameters of the passing strategy  $D_1^{(i)}$ , including some alternative altering course maneuvers, and then, based on the targets and the vessel  $c_3$  behavior, and perform the appropriate option of altering course maneuver.

### 2.8 Methods of accounting the dynamics of vessels while choosing the maneuver

To perform the altering course maneuver it is necessary to calculate the altering course  $K_y$  and the time  $t_y$  of the beginning of the turn according to the Equation 6 (Tsimbal 2007):

$$K_y = K_{oty} + \arcsin[\rho^{-1} \sin(K_c - K_{oty})] \\ K_{oty} = \alpha_y \pm \arcsin \frac{L_d}{L_y} \quad (6)$$

$\alpha_y$  - the value of the bearing to the target at the beginning of the altering course;

$L_y$  - distance to the target at the starting point of altering course;

$L_d$  - the distance of the closest position approach.

Next step is calculating the meaning of  $t_y$  (see Equation 7):

$$t_y = \hat{t}_y - \frac{\Delta x \cos K_{oty} - \Delta y \sin K_{oty} + V_c \tau \sin(K_{oty} - K_c)}{V_{otn} \sin(K_{otn} - K_{oty})} \quad (7)$$

$V_c, K_c$  - the speed and heading of the target;

$V_{otn}, K_{otn}$  - the initial value of the relative speed and course;

$\Delta x, \Delta y$  - coordinates the operating of the vessel during the maneuver;

$\tau$  - duration of rotation of the operating of a vessel;

$\hat{t}_y$  - the time of starting the maneuver,

$\hat{t}_y$  is calculated without taking into account the dynamics of the vessel (Equation 8):

$$\hat{t}_y = \frac{L_d + L_n \sin(\alpha_n - K_{oty})}{V_{otn} \sin(K_{otn} - K_{oty})} \quad (8)$$

The values  $\Delta x, \Delta y$  and  $\tau$  in the expression  $t_y$  are defined for the dynamic model describing the motion of the ship. The most adequate process of real turn of the vessel is described by the course changes of the vessel depending on the angle of the rudder (Equation 9):

$$K = K_0 + \omega_r t + (\omega_0 - \omega_1) \left\{ T_1^2 [1 - \exp(-t/T_1)] - T_2^2 [1 - \exp(-t/T_2)] \right\} / (T_1 - T_2) \quad (9)$$

$$\omega_r = k_\omega \beta_k$$

$k_\omega$  - efficiency of the rudder;

$\beta_k$  - the angle of the rudder;

$K_0, \omega_0$  - the initial rate and the angle speed of the operating vessel;

$T_1, T_2$  - the time constant depending on the vessel dynamics.

Duration of rotation  $\tau$  is calculated in Equation 10:

$$\tau = \Delta t_k + \Delta t \quad (10)$$

where,

$$\begin{aligned} \Delta t_k &= \Delta t + \left\{ T_1^2 [1 - \exp(-\Delta t_k / T_1)] - T_2^2 [1 - \exp(-\Delta t_k / T_2)] \right\} / (T_1 - T_2) - \\ &- \left\{ 2 - [ T_1 \exp(-\Delta t_k / T_1) - T_2 \exp(-\Delta t_k / T_2) ] / (T_1 - T_2) \right\} \times \\ &\left\{ T_1^2 [1 - \exp(-\Delta t / T_1)] - T_2^2 [1 - \exp(-\Delta t / T_2)] \right\} / (T_1 - T_2) \\ &+ \Delta K / \mathbf{a}_\omega, \\ \Delta t &= -T_1 \ln \left\{ (T_2 / T_1) \exp(-\Delta t / T_2) + [(T_1 - T_2) / T_1] L^{-1} \right\} \\ L &= 2 - [ T_1 \exp(-\Delta t_k / T_1) - T_2 \exp(-\Delta t_k / T_2) ] / (T_1 - T_2) \end{aligned}$$

The values  $\Delta t_k$  and  $\Delta t$  are calculated by the method of simple iterations.

The coordinates of the operating vessel during the turning we calculate in Equation 11 and 11 a:

$$\Delta x = \int_0^\tau V_0 \sin[K_0 + K(t)] dt, \quad (11)$$

$$\Delta y = \int_0^\tau V_0 \cos[K_0 + K(t)] dt \quad (11a)$$

### 3 CONCLUSION

The obtained value  $\Delta x, \Delta y$  and  $\tau$  allow to calculate the time  $t_y$  of the beginning of the turn, taking into account the dynamics of the vessel.

### REFERENCES

- Burmaka, I.A., Pyatakov, E.N. & Bulgakov, A.Yu. 2016. Upravleniye sudami v situatsii opasnogo sblizheniya. Germany: LAP Lambert Academic Publishing.
- COLREG - 72. 1972. Odessa: Phenix.
- Pyatakov, E.N., Buzhbetskiy, R.Y., Burmaka, I.A. & Bulgakov, A.Y. 2015. Vzaimodeistvie sudov priraskhozhdenii dlya preduprezhdeniya stolknoveniya. Kherson: Grin.
- Tsimbal, N.N., Burmaka, I.A. & Tupikov, E.E. 2007. Gibkiestrategii rashozhdeniya sudov. Odessa: KP OGT.