

## 1. Introduction

In the practice of navigation, situations arise that require the ship to stop at a given point, for example, to go to the anchorage or to receive a pilot. Considering that the ship has a large inertia, its braking should be done in advance.

Papers [1–3] are devoted to the study of the curvilinear movement of the ship when turning. The formation of the transitional trajectory of the ship's turn taking into account the experimental data of the ship's turnability is considered in [1], and in [2] the results of an experimental study of the ship's turnability models are presented. In work [3] the characteristics of the turnability of the container ship "Oxford" are given and the simulation of its turn is considered.

In work [4] it is noted that the increase in the carrying capacity of modern ships necessitates the use of advanced computer systems for their safe navigation. Such systems use predictive ship traffic instruments that have been successfully used for a long time. However, the simplification of existing forecasts limits their use in terms of immediately displaying the movement of the ship when changing the rudder position and engine speed. The required accuracy of the implementation of the curvilinear trajectory of the ship's movement can be provided by improved predictive models of the ship's movement.

At present, as indicated in [5], an information system is being developed for simulating the movement of ships with complex dynamic models, depending on the rudder angle and engine speed. This system will provide a new type of planning of ship maneuvers and control over the implementation of a given maneuver. It is provided in the process of maneuvering to display the specified maneuvers simultaneously with the actual movement of the ship and with the indication of the predicted trajectory, which is determined

by the real input data from the sensors of the ship. It should be noted that such a system solves the direct problem of displaying the predicted trajectory according to the given parameters

## MANEUVER FOR STOPPING THE SHIP IN A SET POINT BY ACTIVE OR PASSIVE BRAKING AND CONSIDERING THE CURRENT

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**Abstract:** The article deals with the use of active or passive braking of a ship to stop it at a given point. To substantiate the relevance of the study, an analysis of the literature on the problem of ensuring the safe maneuvering of ships was carried out, in which the issues of theoretical and experimental studies of the turnability of ships, the adequacy of the existing models of turnability to the real process of turning the ship, as well as the development of a system of autopilot control of the ship's heading using the principles of fuzzy logic were considered. Considerable attention is paid to the development of an information system for simulating the movement of ships with complex dynamic models.

The necessary analytical expressions are given that characterize the dependences of the time and the distance traveled to the stop of the ship on the mode of active and passive braking, which are required to solve the problem posed in the work.

A formal description of the maneuver for stopping the ship at a given point by active and passive braking is obtained. This description makes it possible to determine the moment of engine stop in case of passive braking or the moment of its reverse – in case of active braking, provided that the ship is following a heading equal to the bearing to a given point.

Cases of presence and absence of current in the area of ship maneuver are considered. In the case of the presence of a current, two stages of the ship's movement are considered: from the zero moment of time until the moment of the start of braking, when the speed of the ship is unchanged, and the second stage, from the moment of the start of braking until the stop of the ship, when the speed of the ship decreases.

To take into account the flow during braking with an exit to a given point, two methods are proposed. The first one is at a constant flow angle with a lateral displacement relative to the programmed trajectory of motion. And the second – with a variable flow angle at zero displacement relative to it.

A successful check of the correctness of the results obtained by simulation computer modeling of maneuvers for stopping the ship at a given point of braking, taking into account the current, has been carried out.

**Keywords:** stopping the ship, active and passive braking, flow accounting, computer simulation.

of the maneuver, although the inverse problem of determining the parameters of the upcoming maneuver along a given programmed trajectory is relevant. In other words, it is necessary to calculate the moment of time of the beginning of the turn and its duration for a given angle of laying of the rudder blade, ensuring the exit of the ship to a given point.

The work [6] is devoted to the issues of identification of ship maneuvering models, which are the key to the study of ship maneuverability, the design of ship traffic control systems and the development of ship simulator control systems. In this paper, based on the analysis of the hydrodynamics of the ship, a nonlinear model of the ship's maneuvering is formed. The system identification theory is used to estimate the parameters of the model, for the calculation of which an algorithm based on the extended Kalman filter theory is proposed. To obtain the input and output data of the system, which are necessary for identifying the parameters of the experiment, circulation and zigzag maneuver are used, which are performed on the ship control simulator. This algorithm eliminates errors introduced during the measurement process.

In [7], the author considers an intelligent system for predicting the movement of a ship, which simulates the learning process of an autonomous control unit, created using an artificial neural network. The control unit observes the input signals and calculates the values of the required parameters for maneuvering the ship in confined waters. The main task of the system is to continuously monitor the navigation parameters of the ship and forecast their values after a certain time interval. The forecast result can be used as a warning to the ship driver about an emerging threat.

Many works on the problem of ensuring the safe maneuvering of ships are devoted to the issues of divergence of dangerously approaching ships. Thus, the principles of locally independent and

external control of the process of divergence of dangerously approaching ships are considered in [8], and promising topical ways to improve the safety of preventing collisions of ships are considered.

In [9], the methods of the theory of optimal discrete processes are used to select a divergence strategy for a ship with several goals, and to describe the interaction of ships with a divergence in [10], it is proposed to use the method of nonlinear integral invariance.

A universal method of preventing a collision of a ship with several targets by shifting to a parallel track line is proposed in the monograph [11], and in [12] the problem of preventing collisions of ships is studied in detail and the concept of flexible strategies for their divergence is developed.

The analysis shows that the issues of braking the ship with a stop at a given point have not been considered previously. This determines the aim of the proposed study, and it is necessary to formalize the execution of the maneuver in the presence and absence of a flow.

**2. Methods**

To solve this problem, analytical expressions are necessary that characterize the dependences of time  $t_s$  and distance  $S_s$  traveled to stop the ship from the braking mode (active or passive).

Using the results of work [8], **Table 1** shows the design formulas  $t_s$  and  $S_s$  for the ship in different modes of braking.

**Table 1**  
Design formulas  $t_s$  and  $S_s$  of the ship in different braking modes

Braking elements	Active braking	Passive braking
Current speed	$V_a = \frac{\sqrt{P}}{\sqrt{\mu}} \operatorname{tg} \left[ \operatorname{arctg} \left( \frac{\sqrt{\mu}}{\sqrt{P}} V_o \right) - \frac{\sqrt{\mu P}}{(1+k)m} t \right]$	$V_p = \frac{V_o}{1 + \frac{V_o \mu}{(1+k)m} t}$
Braking time	$t_a = \frac{(1+k)m}{\sqrt{\mu P}} \operatorname{arctg} \left( \frac{\sqrt{\mu}}{\sqrt{P}} V_o \right)$	$t_p = \frac{(1+k)m}{\mu V_o} \left( \frac{V_o}{V_k} - 1 \right)$
Distance	$S_a = \frac{(1+k)m}{2\mu} \ln \left  1 + \frac{\mu}{P} V_o^2 \right $	$S_p = \frac{(1+k)m}{2\mu} \ln \left  \frac{V_o^2}{V_k^2} \right $

In the above expressions:

- $m$  – mass of the ship with attached masses of water;
- $\mu$  – resistance coefficient;
- $P$  – screw stop;
- $V_o$  – initial ship speed;
- $V_k=1\div 2$  knots.

**3. Results**

In this section, let's consider an analytical description of the maneuver for stopping the ship at a given point by active or passive braking, and it is required to determine the time of stopping the engine during passive braking or the moment of its reverse – during active braking.

Let's consider the calculation of the start time of the ship's braking to stop it at a given point, and the ship follows a heading equal to the bearing to a given point.

Let's first consider the case when there is no current in the area of the ship's maneuver. The initial data are used to calculate the braking time  $t_s$  and distance  $S_s$ . If to denote the distance at the initial moment of time to the stopping point through  $D$ , then, obviously, the moment of the start of braking is determined by the following expression:

$$t_n = \frac{D - S_s}{V_v},$$

where  $V_v$  – ship's speed.

In the case of a current, two stages of the ship's movement should be considered: from the zero moment of time to the moment of the start of braking, when the speed of the ship is unchanged, and the second stage from the moment of the start of braking until the stop of the ship, when the ship's speed decreases (**Fig. 1**).

To solve the problem, it is first necessary to determine the distance  $S_\Sigma$ , for which let's consider the triangle DEF. In this triangle  $S_s$  is the braking distance, and the distance  $S_T$  characterizes the drift of the ship by the current during the braking time  $t_s$ , and the following expression is obvious:  $S_T = V_T t_s$ , where  $V_T$  is the current speed.

The drift angle can be found from the ratio:

$$\frac{\sin \beta}{\sin \alpha} = \frac{S_T}{S_s}, \quad \beta = \arcsin \left( \frac{S_T}{S_s} \sin \alpha \right).$$

In the last expressions  $\sin \alpha = |\sin(K_T - K_V)|$ , where  $K_V$  – programmed heading of the ship;  $K_T$  – flow direction.

By the cosine theorem from the triangle DEF:

$$S_\Sigma = \sqrt{S_T^2 + S_s^2 - 2S_T S_s \cos(\pi - \alpha - \beta)}.$$

From **Fig. 1**:

$$t_n = \frac{D - S_\Sigma}{V_\Sigma}, \tag{1}$$

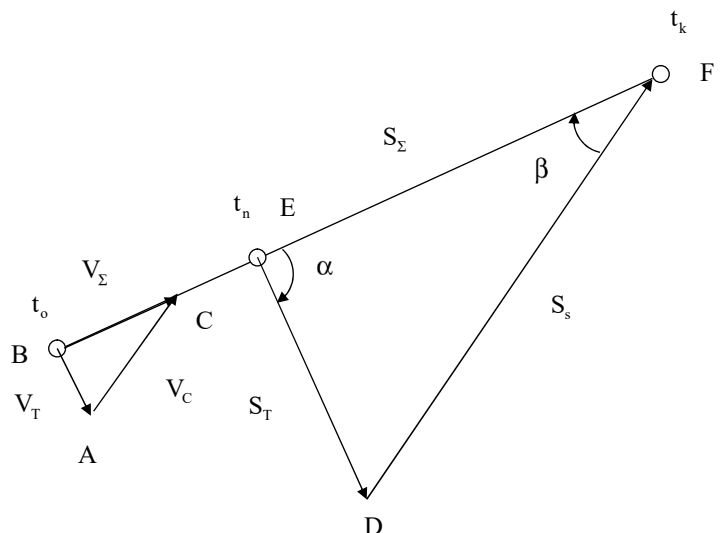
where  $V_\Sigma$  – speed of the ship along the programmed trajectory.

Let's find an expression for the speed  $V_\Sigma$ , introducing the notation for the angles:

$$\alpha_1 = \angle ABC \text{ and } \beta_1 = \angle BCA.$$

Let's note that  $\alpha_1 = \alpha$ . It's obvious that

$$\beta_1 = \arcsin \left( \frac{V_T}{V_C} \sin \alpha \right).$$



**Fig. 1.** Influence of the current on the ship braking process

Also, by the cosine theorem from the triangle ABC:

$$V_{\Sigma} = \sqrt{V_T^2 + V_C^2 - 2V_T V_C \cos(\pi - \alpha - \beta_1)}$$

Using formula (1), let's calculate the braking start time  $t_n$  in the presence of flow. The braking end time  $t_k$  is calculated using the expression:

$$t_k = t_n + t_s.$$

Let's note that at the first stage, from the zero moment of time  $t_0$  to the moment of the braking start  $t_n$ , the ship's heading  $K_C$  is equal  $K_C = K_V + \beta_1$ , and in the second stage, from the moment in time  $t_n$  to the moment in time  $t_k$ , the ship must follow the heading  $K_C = K_V + \beta$ .

In the considered case, the flow during braking was taken into account by choosing the value of the angle  $\beta$ , at which the displacement from the programmed trajectory of the ship during the braking time is equal to the drift from the current, but has the opposite sign. As a result, by the moment of stopping, the ship is at the given point.

However, when braking, the ship does not move along the programmed trajectory, it first shifts relative to the programmed trajectory in the direction opposite to the direction of the current, and then when the ship's speed decreases, the displacement decreases and turns to zero by the moment the braking is completed.

The current value of the current angle can be found using the expression:

$$\beta_t = \arcsin\left(\frac{V_T}{V_t} \sin \alpha\right),$$

where  $V_t$  – current value of the ship's speed.

In the case of passive braking, let's obtain the expression:

$$\beta_t = \arcsin\left(\frac{V_T}{\left(\frac{V_0}{1 + \frac{V_0 \mu}{(1+k)m} t}\right)} \sin \alpha\right),$$

and with active braking to keep the ship on the programmed trajectory of movement, the angle of the current  $\beta_t$  must be changed according to the following formula:

$$\beta_t = \arcsin\left(\frac{V_T}{\left(\frac{\sqrt{P}}{\sqrt{\mu}} \operatorname{tg}\left[\arctg\left(\frac{\sqrt{\mu}}{\sqrt{P}} V_0\right) - \frac{\sqrt{\mu P}}{(1+k)m} t\right]\right)} \times \sin \alpha\right).$$

Obviously, in order for the ship to remain on the programmed trajectory of movement during braking, it is necessary to change the current angle, increasing it with a decrease in the ship's speed.

#### 4. Discussion

To check the correctness of the obtained results, a computer simulation of the ship's stopping maneuvers at a given braking point, taking into account the current, was carried out.

Fig. 2 shows a maneuver for stopping a ship by passive braking, and for the simulation, the ship's heading was 45°, its speed was 18 knots, the direction of the current was 315°, and the current speed was 4 knots. The starting position of the boat is shown with a red circle and the start of braking is shown with yellow. The blue color shows the braking trajectory with a constant angle of flow, and the red color – with a variable angle.

The results of simulation by active braking are shown in Fig. 3. For the simulation, the following initial data were selected: the heading and speed of the ship, respectively, 120 and 25 knots, the direction and speed of the current 205° and 4.5 knots, the distance to the complete stop of the ship is 3 miles, the speed of the ship at the braking end is zero.

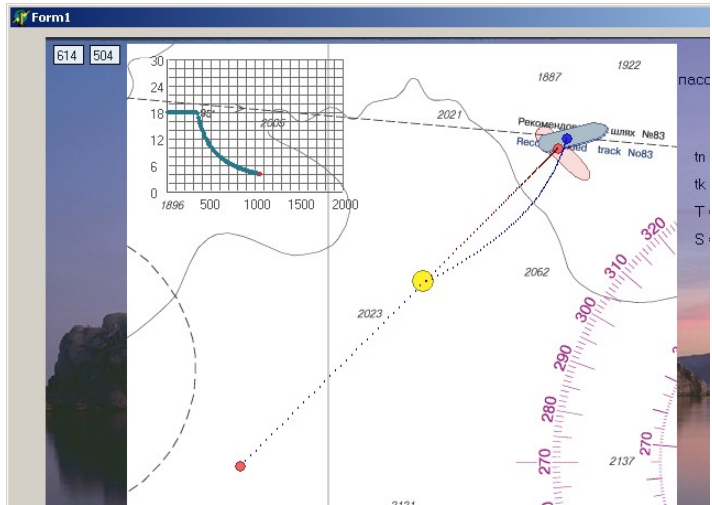


Fig. 2. Replaying the passive braking maneuver

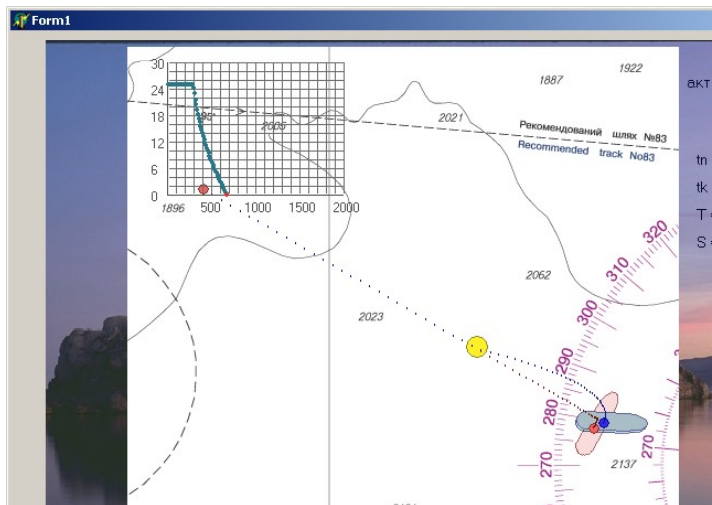


Fig. 3. Replaying the active braking maneuver

#### 5. Conclusions

Thus, taking into account the flow during braking with an exit to a given point is possible using two methods: with a constant flow angle with the presence of lateral displacement relative to the programmed motion trajectory and with a variable flow angle at zero displacement.

These methods can be used in electronic navigation systems for controlling the movement of a ship for preliminary and advance replaying of various maneuver options, as well as in coastal navigation systems for ensuring the safety of navigation.

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