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# Ship Track and Speed Model in Case of Steering Gear Breakdown with Rudder Remaining Fix at non Zero Angle

Original scientific paper

Ship navigation is determined by the ship's position on a certain part of the fairway from the place of departure to the place of arrival. During the voyage, in a given period of time ship changes the course and the speed. Navigation itself can be viewed from the aspect when during the voyage all onboard systems are functioning properly and the person managing the ship practices good seamanship, and from the aspect when an extraordinary event occurs, which affects the possibility of maintaining the desired course and/or speed.

This paper analyzes the movement of the ship in case of an extraordinary event with the assumption that the malfunction occurred in the steering system. Depending on the navigation area and the sea traffic, such an event generates two basic maritime navigation risks, the risk of ship grounding and the risk of collision. This paper explores ship movement that, depending on the scenario, may result in ship grounding.

For the purposes of conducting research on ship movement due to the assumed extraordinary event onboard, various scenarios were defined. To create a track model, an Euler spiral/clothoid was chosen. By modifying the parametric clothoid equation, a curve was obtained which very well approximated the curve of a turning ship. Furthermore, developed was the speed change model that can show the speed change at any point of the curve of a turning ship when the rudder deflection was constant, and the engine was stopped. The designed models were tested in 60 scenarios in accordance to which the research on the navigation simulator was carried out.

Ship track model can be used in the field of research for simulation model development, the result of which will enable determining the extent of grounding damage, and after determining the extent of grounding consequences, it will enable the defining of acceptable risk as well.

**Keywords:** *extraordinary event, ship track model, speed change model, risk of grounding*

## Model kretanja i brzine broda u slučaju zakazivanja kormilarskog uređaja sa zakrenutim kormilom

Izvorni znanstveni rad

Plovidba broda određena je položajem broda na određenom dijelu plovnog puta od mjesta polaska do mjesta dolaska. Tijekom plovidbe brod mijenja smjer i brzinu u nekom vremenu. Sama plovidba može se razmatrati s aspekta kada tijekom plovidbe svi sustavi na brodu rade ispravno, a osoba koja upravlja brodom se ponaša kao „dobar pomorac“ i s aspekta kada je tijekom plovidbe došlo do nastanka izvanrednog događaja koji utječe na mogućnost održavanja željenog smjera i/ili brzine.

U ovom radu istraženo je kretanje broda pri nastanku izvanrednog događaja, a pretpostavlja se da je kvar nastao na sustavu kormilarenja. Ovisno o području u kojem brod plovi i količini pomorskog prometa takav događaj generira dva osnovna pomorska plovidbena rizika, rizik nasukanja i rizik sudara. U ovom radu istraženo je kretanje broda koje ovisno o scenariju može rezultirati nasukanjem broda.

Za potrebe istraživanja kretanja broda zbog pretpostavljenog izvanrednog događaja na brodu definirani su različiti scenariji. Za izradu modela krivulje kretanja broda s obzirom na definirane scenarije izabrana je klotoida. Modificiranjem parametarske jednadžbe klotoide u konačnici se dobila krivulja koja vrlo vjerno aproksimira krivulju kretanja broda. Nadalje, izrađen je model promjene brzine koji može procijeniti brzinu broda u bilo kojoj točki krivulje okretanja broda kada je otklon kormila konstantan, a stroj zaustavljen. Dobiveni modeli ispitani su na 60 scenarija prema kojima je provedeno istraživanje na navigacijskom simulatoru.

Model kretanja broda može se iskoristiti u području istraživanja za razvoj simulacijskog modela čiji će rezultat omogućiti određivanje veličine oštećenja pri nasukanju, a nakon određivanja posljedice nasukanja omogućit će i definiranje prihvatljivog rizika.

**Ključne riječi:** *izvanredni događaj, model krivulje kretanja broda, model promjene brzine, rizik nasukanja*

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## 1 Introduction

Coastal region, sea and islands are among the most valuable and the most vulnerable parts of the Earth and are constantly exposed to negative effects of numerous human activities. Ship navigation, being one of them, in such areas is subject to multitudinous hazards that affect safe navigation and generate certain risks.

One of the potential dangers linked to navigation is grounding, the cause of which is the occurrence of an extraordinary event on board a ship. Grounding of a ship is one of the most common maritime casualties that take place at sea. Although it seldom results in losses of human lives, it can cause pollution with harming consequences for the environment.

In order to decrease the risk of grounding, which results in great ship damage and consequently in great pollution of the environment, it is necessary to investigate ship's motion after the occurrence of an extraordinary event on board. As an extraordinary event, a scenario was assumed in which a malfunction of the steering gear is present, and the rudder remains blocked with a certain angle of deflection. In the chosen scenarios, it is assumed that the ship's crew is not able to fix the breakdown within a short period of time.

In order to obtain the grounding elements, on the basis of which the extent of grounding consequences can be determined, this paper examines the motion of the ships of various characteristics while assuming the occurrence of the previously described extraordinary event. Based on the conclusions regarding the ship motion after the occurrence of the assumed extraordinary event, scenarios were defined and investigated on the navigational simulator Transas Marine Navi-Trainer NTPro 4000 installed at the *Faculty of Maritime Studies* in Rijeka, approved by the *Det Norske Veritas – DNV*, "Class A - Standard for certification of maritime simulators No. 2.14".

Ship motion trajectory can also be obtained *in-situ* by conducting investigate on real ships, performing model testing in towing tanks, and utilizing the existing track models. As the aim of this paper was to obtain the curve of turning ships with satisfactory accuracy in real time using the available data concerning the ship during exploitation, the scenario investigate on the navigational simulator was selected. It should be noted that ship track model was obtained by investigate on the navigational simulator with installed hydrodynamic ship track models, which indirectly entails the hydrodynamic analysis as part of the conducted investigate with accuracy limitations of the simulator's hydrodynamic model.

Another reason for selecting navigational simulator research was the fact that this kind of investigation of motion trajectory of man operated ships, whereby the behaviour of man is analyzed as well as the behaviour of the model.

Although in view of the fundamental aim of this paper the ship track model attained in the described manner can be considered satisfactory, a hydrodynamic analysis should be performed as a continuation of this research in order to additionally verify the obtained ship track model.

Based on the results of the conducted simulations, a ship track model and a speed change model were created. Using these models, the curve of a turning ship for the wanted scenario and the ship speed at any point of the curve of a turning ship are obtained. The model allows for the input values to variate, and the obtained results provide the parameters of ship grounding.

## 2 Analysis of former ship grounding models

Former research concerning ship grounding models was focused on geometric models. The observed models explored physical risks of grounding, while grounding models exploring other risks of grounding (risks concerning individuals, society, property and rights) were not analyzed. The former models were analyzed in the chronological order.

Ship grounding models can generally be divided into two groups:

1. Analytical models, for which ship traffic distribution was not taken into consideration while defining the model,
2. Statistical models, for which ship traffic distribution was taken into consideration while defining the model.

Considering the aim of this paper and the possibilities of comparing the obtained research results with the former models, the following paragraphs contain descriptions of analytical models only.

Macduff [1] concluded that the real probability of grounding is a product of geometric probability and causation probability. He based the development of his model upon the Buffon's needle problem. Macduff displayed the fairway two-dimensionally and the ship one-dimensionally (as a needle or a line). This kind of approach of neglecting the ship's breadth and draught is questionable.

Along with the Macduff's model, Fujii's [2] model was one of the earliest geometric ship grounding models, on the basis of which many models of later investigation were formed. Fujii presented his model as a tool for determining the number of groundings. In his model, fairway depth and ship's draught were not directly used for calculating grounding candidates.

Kite-Powell et al. [3] did not present their model as a geometric grounding model, but as a mathematical model based on the Bayesian theory. Not a single model defining scenario was provided, but it was concluded that the probability of grounding while navigating in a certain area is dependant upon multiple risk factors that represent influential variables. Kite-Powell's grounding model does not provide the number of the grounding candidates, but is a useful model for determining consequential probabilities.

Fowler and Sørgård [4] are the only authors that separated the grounding models for groundings while the propulsion system was working from the models for the groundings caused by external forces. In the first scenario, geometric elements included in the model are the distances between the waypoints and the possible grounding area. In the second scenario, the authors considered the possibility of failure recovery, the possibility of anchoring the ship, and the possibility of tug assistance. They assumed drift speed with regards to wind speed, but did not allow for the effect of the sea current and the waves.

Kristiansen's [5] grounding model can be viewed as a simplified combination of Fujii's model and Macduff's model that also incorporates a model for ship grounding on the shoreline (in the fairway). Kristiansen assumed that the ship is following a course in the so-called critical phase. He defined the critical phase as the case when the ship looses control of manoeuvring due to some technical failures or human error, or both simultaneously. He defined the critical angle $\alpha$ under which ship grounding could take place. Conditional probability of grounding is defined as a ratio of the critical angle $\alpha$ and the total angle for one side of the fairway $\pi/2$. Kristiansen noted that his model was too simplified for real scenarios, but that it could be used for comparison of different scenarios.

In his paper, Galor [6] stated that an extraordinary event can occur due to human error, mechanical failure, and meteomarine conditions. For random variables that are to describe the ship's motion after an emergency, Galor chose the angle $\phi$ that represents the angle between the planned course and the course after the occurrence of the extraordinary event and ship stopping distance. Galor's model is suitable for determining the probability of collision/impact into an obstruction on the fairway, but is not appropriate for determining the probability of grounding on the shoreline in the waterway.

The results of the described models are geometric probabilities of grounding. The geometric probability of grounding is obtained based upon assumptions, such as that the ship is at risk of grounding unless a grounding avoidance action is taken, that the ship will deviate from the course at an angle $\phi$ which will result in grounding, that the ship will cross the fairway border, and that the difference between the ship's breadth and the fairway breadth is greater or smaller, etc. To obtain the results using these models, the authors introduce some parameters that must be assumed. For some assumptions, they rely on statistical data of previous casualties, and some data in statistical data bases are up to 40 years old. Since within those 40 years significant changes have been introduced concerning ship characteristics, equipment, education of mariners, aids to navigation, usage of this data in present conditions is questionable. When the quantity of statistical data is small, which is often the case with maritime casualties, the authors use expert judgment, which is dependent on the expert's abilities, and the data obtained in this manner cannot be verified.

Therefore, it can be concluded that the existing models do not provide a realistic representation of grounding and should be further developed.

## 3 Analysis of the curve of a turning ship

The basic assumption of the motion of ship's movement is an occurrence of an extraordinary event, i.e. failure of the steering system that resulted in a certain angle of rudder deflection. It is also assumed that the ship's crew is not able to recover the failure within a short period of time. The consequence of the failure, i.e. a certain rudder deflection, will be a turning moment that will cause ship turning.

While analyzing ship turning, due to the effect of the rudder, three characteristic phases shown in Figure 1 are identified:

1. The time from the moment of the rudder deflection until the moment when the ship starts turning. Rudder force is the result of the rudder deflection by an angle $\alpha$. One of its components is undesirable because it increases the ship's resistance, while the other component creates a transverse force on the ship's longitudinal axis along with a simultaneous moment with regard to the current position of the pivot point. Before the ship starts turning, the mentioned moment induced by rudder force action must overcome the inertial moment due to the ship's own mass and the addes mass. Before it overcomes the mass moment of inertia, the effect of the transverse component manifests only in moving the entire ship sideways, in a direction perpendicular to the ship's longitudinal axis. The first phase lasts a short period of time, and the movement is greater on the stern than it is on the bow. Thus, immediately after the rudder deflection, the ship's motion is at first opposite from the desired one.

2. The second phase begins with the turning of the ship's bow in the desired direction, at the moment when the rudder force moment overcomes the intertial moment due to the ship's own mass and the added mass. During the second phase, ship speed decreases, the rate of turn increases, and the radius of the turning circle decreases. The ship continues to turn in a curve, the curvature radius of which decreases, and during the turning, the bow is always closer to the centre of the circle than the stern.

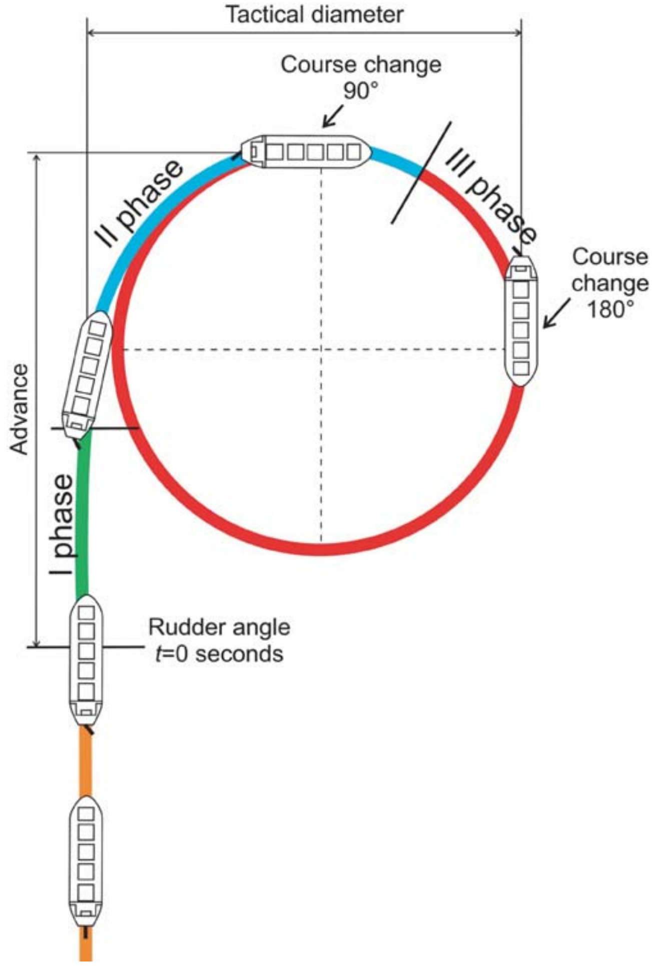



Figure 1 **Characteristic phases of ship turning**
Slika 1 **Karakteristična razdoblja pri okretanju broda**

3. The third phase begins at the moment when all the forces and moments (ship's resistance force, propulsion force, rudder's moment of force, inertial forces and moments) are balanced. Then the ship starts turning with a constant speed in a circle of a constant radius. The bow continues to turn in a circle of a shorter radius than that of the stern. This phase of ship turning usually begins after the ship changed its course by 100° to 120°.

## 4 The method for selecting the curve of a turning ship

Keeping the principles of the ship's motion during turning in mind, it was necessary to define a curve that best describes the ship's turning trajectory. At the same time, the curve had to meet two conditions:

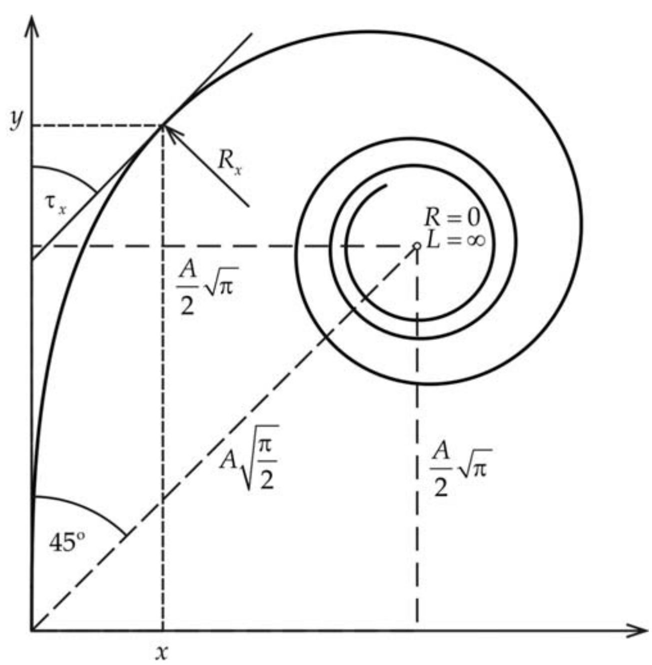
- approximate the curve of a turning ship as close as possible,
- have parameters (elements) that can be attributed to some characteristic property of the turning ship.

The possibility of grounding in case of the described extraordinary event depends on the transfer of the ship and the distance between the grounding isobath and the ship's position at the moment of occurrence of the extraordinary event. When the maximum transfer is shorter than the distance from the grounding isobath, it is evident that grounding will not take place. Therefore, while defining the curve that will approximate the curve of a turning ship best, the part of the curve of a turning ship to its maximum transfer was taken into consideration. From the above mentioned description of the characteristic phases of the ship turning due to rudder deflection, it can be concluded that the approximated part of the curve of a turning ship will contain all three turning phases. The maximum transfer is dependant on a number of factors, and it will certainly not occur with a course change of 180°, but with a somewhat greater course change.

Among all the analyzed curves, the Euler spiral/clothoid was identified as the curve that has the most similar principals to those of the curve of a turning ship. Clothoid is used in roads and railways engineering. In road-rail transport, straight and curved parts of roads/railways constantly interchange. Curved parts are set by the curvature radius, and the vehicle then moves in an arc. The problem lies at the junction of the straight part (line) and the curved part (arc).

Thus, at this junction a clothoid is used, and a gradual transition from a line into a circle is made. Meanwhile, the curvature radius constantly decreases until it reaches the length of the radius of the curvature circle, and this change is linear.

Figure 2 **Mathematical form of the clothoid**
Slika 2 **Matematički oblik klotoide**




The clothoid has a spiral shape and, compared to a circle, is more complex by just one degree, Figure 2. For the clothoid it stands that:

$$R \cdot L = Const. = A^2 \quad (1)$$

or:

$$A = \sqrt{R \cdot L} \quad (2)$$

where:
$R$ - the clothoid curvature radius at a given point,
$L$ - the length of the clothoid arc from the starting point to a given point,
$A$ - the parameter of the clothoid.

The parameter of the clothoid $A$ represents the scale factor. If the parameter $A$ changes, the size of the clothoid changes as well. Parameter $A$ has the same meaning as radius $R$ for the arc or parameter $p$ for the parabola and the hyperbola. Its increase or decrease only changes the size, but the shape always remains similar, as shown in Figure 3. This means that all clothoids are geometrically similar, and can practically be translated one over another by photographic enlargement or reduction.

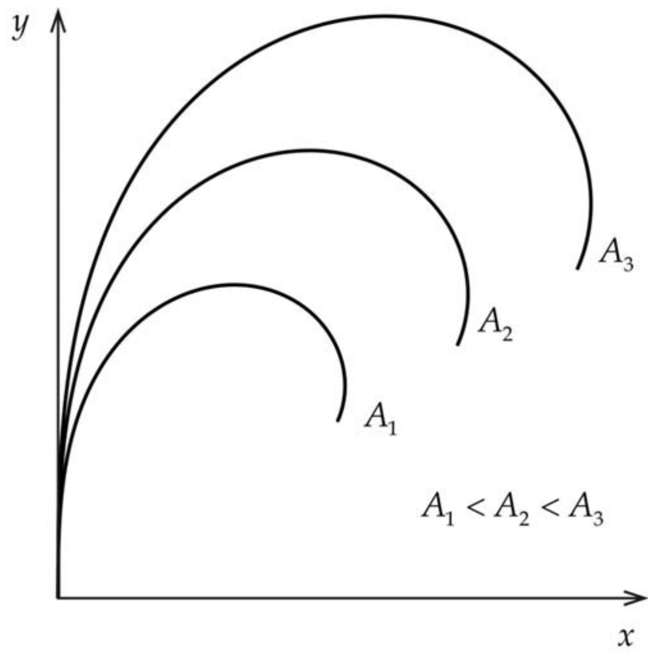



Figure 3 **Geometrically similar clothoids dependent on the parameter *A***
Slika 3 **Geometrijski slične klotoide ovisne o parametru *A***

A comparison of the curve of a turning ship with the clothoid leads to the conclusion that in the first phase of the ship's turning, a small course change occurs which corresponds to a small variation of curvature radius at the initial phase of the clothoid. In the second phase of the ship's turning, a constant decrease of curvature radius is present, along with an increase of the angular speed, which similarly takes place with the clothoid as well, because a uniform linear variation of curvature and a decrease

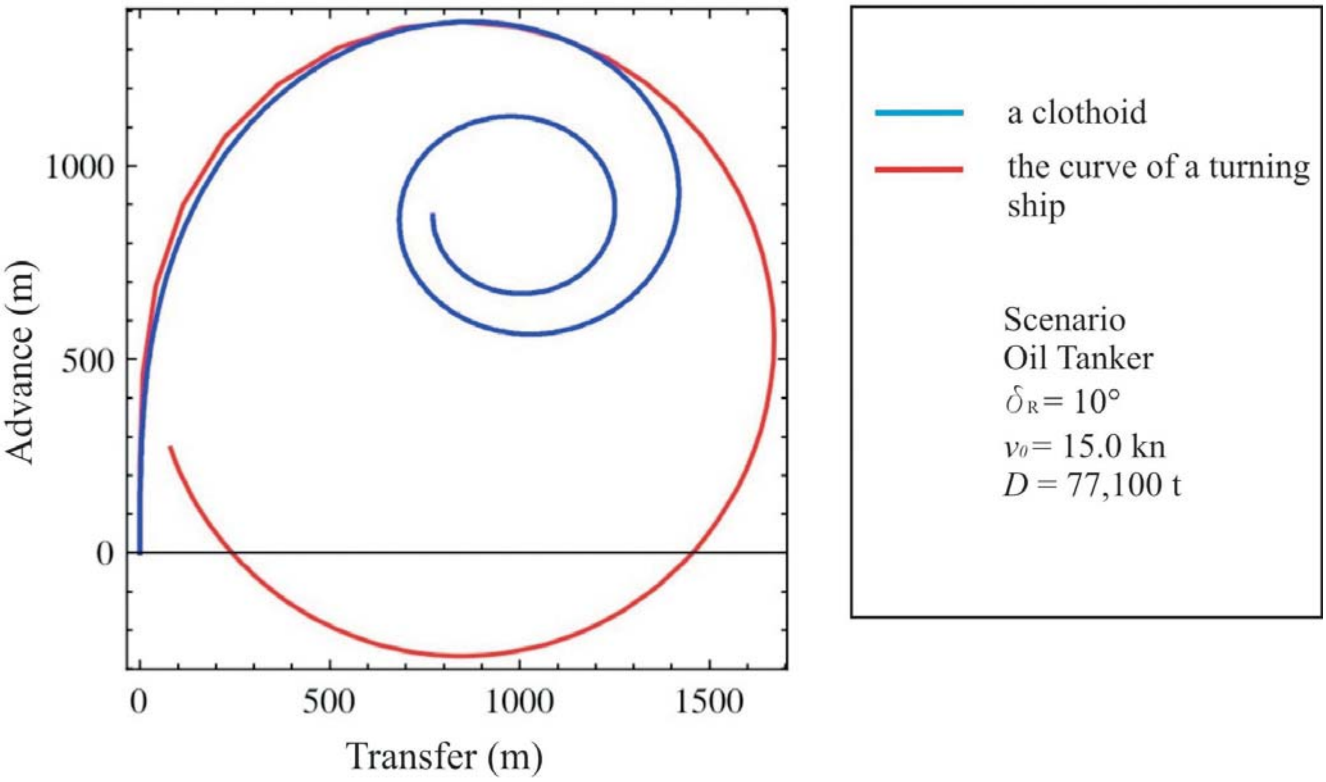



Figure 4 **Comparison of a clothoid with the curve of a turning ship**
Slika 4 **Usporedba klotoide i krivulje okretanja broda**

in radius occur. In the third phase, ship turns with a constant rate of turn and a constant radius, which is not the case with the clothoid, where an variation of curvature and a decrease in radius remain.

Thus, it can be concluded that in the first and the second phases, the clothoid approximates the curve of a turning ship very well, but in the third phase the principles of a circle should be applied, Figure 4. This is theoretically possible and should result in a very good approximation of the curve of a turning ship. While selecting the curve, the second condition should be met, i.e. that the parameters of the selected curve can be attributed to some characteristic property of the turning ship. The above mentioned combination, however, does not meet that condition. Thus, a modified clothoid was selected in order to better approximate the curve of a turning ship and also meet the conditions listed above.

In the literature [7], various forms of parametric equations of the clothoid are mentioned, but the following generalized form was selected for purposes of this paper:

$$x(t) = a\int_0^t \sin\left(\alpha\tau^2\right)\mathrm{d}\tau$$
$$y(t) = b\int_0^t \cos\left(\beta\tau^2\right)\mathrm{d}\tau \qquad (3)$$

The generalization refers to the possibility of using different coefficients $\alpha$ and $\beta$ for purposes of greater flexibility in modelling a real trajectory of a ship. At the same time, one of the criteria for generalization was to generate as few free parameters that have no physical meaning as possible.

Constants of multiplication $a$ and $b$ affect scaling of the clothoid on the XY plane. They can be changed into $a \to ax_{max}$ and $b \to by_{max}$ in order to achieve scaling of the clothoid to a universal unit size using $a$ and $b$, and an additional scaling to the real curve of the ship's trajectory using $x_{max}$ and $y_{max}$. At the same time, this achieves a clearer effect of sensible (input) parameters with no consequences to mathematical formalism. The introduced parameters have the following meanings:

$x_{max}$ - maximum transfer, and
$y_{max}$ - maximum advance.

The expressions (3) change into the following form:

$$x(t) = a x_{max}\int_0^t \sin\left(\alpha\tau^2\right)\mathrm{d}\tau$$
$$y(t) = b y_{max}\int_0^t \cos\left(\beta\tau^2\right)\mathrm{d}\tau \qquad (4)$$

The following points are selected as characteristic points that can be used in adjusting the ship's trajectory:

$T_{x_{max}}$ - as the point at which the $x$-coordinate reaches a global maximum (the tangent parallel to the $y$-axis), and
$T_{y_{max}}$ - as the point at which the $y$-coordinate reaches a global maximum (the tangent parallel to the $x$-axis).

The exact calculation of the parameter $t_{x_{max}}$ and $t_{y_{max}}$ that corresponds to those points is obtained based on the condition that the first derivatives of the corresponding coordinate according to the parameter $t$ are equal to 0 (extreme value condition):

$$\left(\frac{dx}{dt}\right)_{t_{x_{max}}} = 0 \qquad \left(\frac{dy}{dt}\right)_{t_{y_{max}}} = 0 \tag{5}$$

which, according to the clothoid equation, leads to:

$$a\,x_{max}\sin\left(\alpha t_{x_{max}}^2\right) = 0 \qquad b\,y_{max}\cos\left(\beta t_{y_{max}}^2\right) = 0 \tag{6}$$

that is:

$$\alpha t_{x_{max}}^2 = k\pi, \quad k = 0, \pm 1, \pm 2, \dots \qquad \beta t_{y_{max}}^2 = \frac{\pi}{2} + k\pi, \quad k = 0, \pm 1, \pm 2, \dots \tag{7}$$

The global extreme is obtained by the selection $k$ = 1, and, $k$ = 0 hence:

$$t_{x_{max}} = \sqrt{\frac{\pi}{\alpha}} \qquad t_{y_{max}} = \sqrt{\frac{\pi}{2\beta}} \tag{8}$$

The constants $a$ and $b$ introduced in (4) are obtained from the requirement that the clothoid reaches global extremes at the points $T_{x_{max}}$ and $T_{y_{max}}$:

$$x\left(t_{x_{max}}\right) = x_{max} \qquad y\left(t_{y_{max}}\right) = y_{max} \tag{9}$$

therefore:

$$x_{max} = a\,x_{max}\int_0^{t_{x_{max}}} \sin\left(\alpha\tau^2\right)\mathrm{d}\tau \qquad y_{max} = b\,y_{max}\int_0^{t_{y_{max}}} \cos\left(\beta\tau^2\right)\mathrm{d}\tau \tag{10}$$

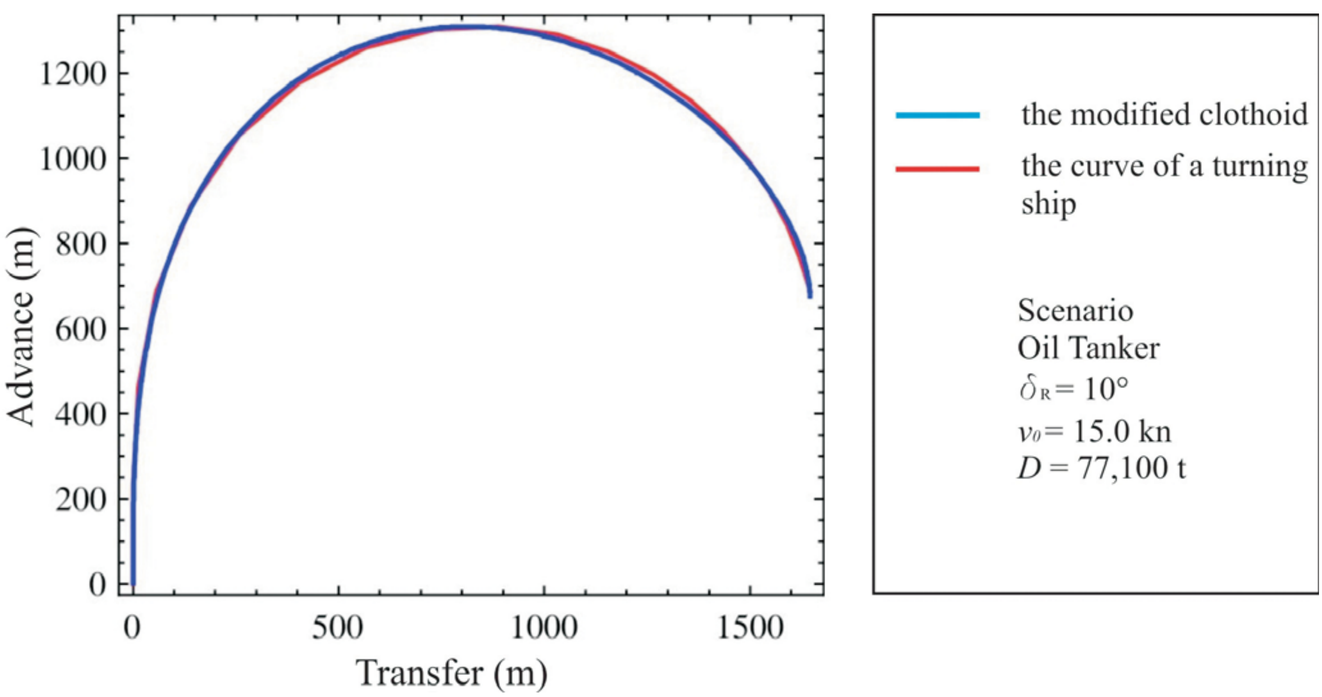
and:

$$a = \left[\int_0^{\sqrt{\pi/\alpha}} \sin\left(\alpha\tau^2\right)\mathrm{d}\tau\right]^{-1} \qquad b = \left[\int_0^{\sqrt{\pi/(2\beta)}} \cos\left(\beta\tau^2\right)\mathrm{d}\tau\right]^{-1} \tag{11}$$

In a thorough analysis of the values of the parameters $\alpha$ and $\beta$, in order to obtain an optimal approximation of the curves of a turning ship, a conclusion was reached that the values are:

$$\alpha = 1.0$$
$$\beta = 1.2$$

Figure 5 **The achieved fit of the model of a turning ship with the real curve of a turning ship**
Slika 5 **Postignuto poklapanje modela kretanja broda sa stvarnom krivuljom kretanja broda**



The values selected in this manner result in:

$$a = 1.11753$$
$$b = 1.2072$$

The achieved fit of the model of a turning ship with the real curve of a turning ship is shown in Figure 5.

While analyzing the values of the parameters $\alpha$ and $\beta$, in order to achieve the best fit of the model and the curve of the ship's trajectory, it was noticed that the parameter $\beta$ is more responsive. By changing the parameter $\beta$ in the model, better approximations were achieved with some curves of a turning ship. The value of the parameter $\beta$ varied from 1.16 to 1.20. As the difference in shape between the curve obtained by the model and the real curve of a turning ship is small regardless the change in the parameter $\beta$ (from 1.16 to 1.20), and the effect on the final result is even smaller, the value of 1.20 was chosen as the best general value of the parameter $\beta$.

## 5 Speed change model

After creating the track model, it was necessary to create a speed change model as well. While selecting a speed change model, the existing models could not be used, because they model a decrease in speed with linear motion. For purposes of this paper, the speed change at any point of the curve of a turning ship for a given constant rudder deflection had to be determined.

Another particularity while defining the speed change model was the assumption that, after the occurrence of the emergency (malfunction of the steering gear) that resulted in a certain rudder deflection, the ship's crew would stop the engine in order to reduce the consequences in case of ship grounding. Therefore, the speed change model must show the speed change at any point of the curve of a turning ship when the rudder deflection is constant and the engine stopped.

In order to meet these requirements, it was necessary to create a model in which speed tends to zero when time tends to infinity. At $t = 0$, the model has to fulfil the condition of $v = v_0$ *(initial speed)*. At the moment of $t = 0$ and at a certain initial speed $v_0$, it is assumed that a certain rudder deflection angle is present due to the malfunction of the steering system, and that the crew stopped the engine.

Creation of the speed change model was based on the assumption that the resistance force is proportional to speed (more generally a resistant is proportional to some power of speed), and by adapting this model with the simulated speed function, the following expression was obtained:

$$v(t) = \frac{v_0}{\sqrt{1 + wt^2}} \qquad (12)$$

where:

$v(t)$ - ship speed (m/s),

$t$ - time measured from the moment when the extraordinary event occurred (s),

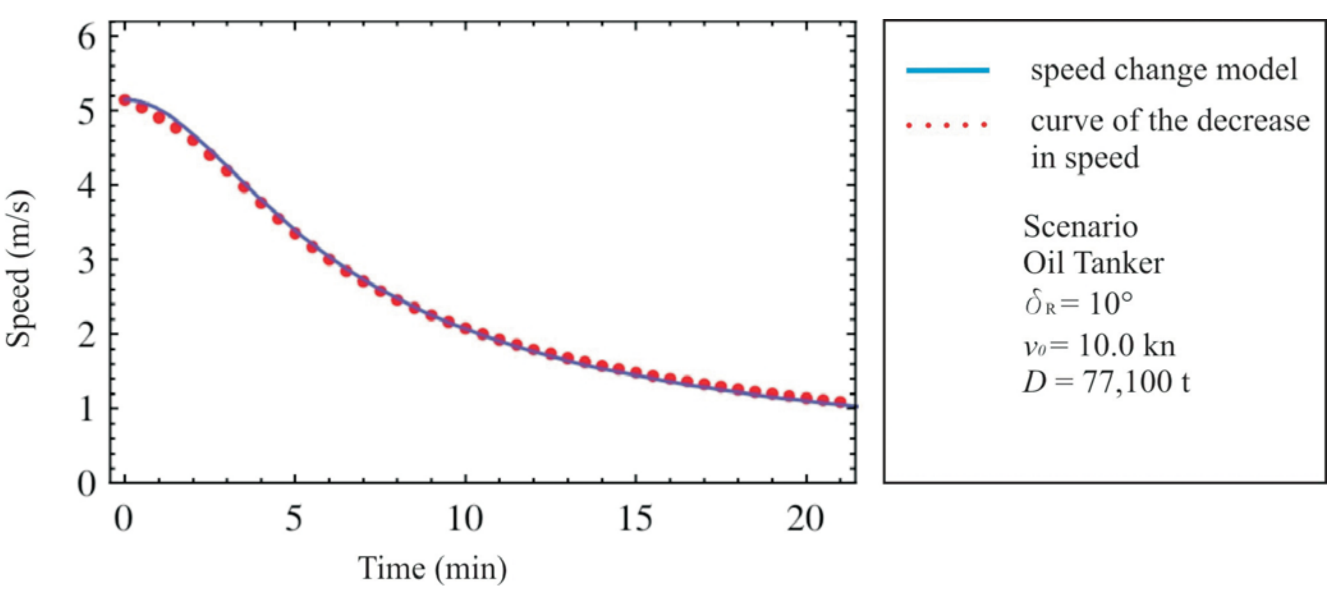
$v_0$ - initial speed at which the extraordinary event occurred (m/s),

$w$ - parameter linked to the resistance of the ship in water ($s^{-2}$).

The displayed model optimally approximated the decrease in ship speed until the crucial phase of the ship's turning. In the model, the initial speed $v_0$ is one of the parameters and is defined as input data.

The second parameter $w$ is linked to the resistance of the ship moving through the water, and thus dependent on the deflection of the blocked rudder. Besides the data set $(x,y)$ that represents the trajectory, the $(v,t)$ data that represent speed decrease in time are also taken into consideration for each specified scenario. The value of the parameter $w$ is obtained by the method of least squares. This procedure must be applied to all simulated trajectories, and the $w$ parameters obtained in this manner are stored

Figure 6 **The achieved fit of the speed change model with the simulated speed function**
Slika 6 **Postignuto poklapanje modela promjene brzine sa simuliranom funkcijom brzine**



and later used in speed decrease modelling in a given scenario. The achieved fit of the speed change model with the simulated speed function is shown in Figure 6.

The achieved fit of the ship track model and the speed change model with the real curve of a turning ship was examined on 60 selected scenarios. Research was conducted on two types of ships (tankers and bulk carriers) and five characteristic ship sizes (from 44,288 t of displacement to 321,260 t of displacement). Four degrees of rudder deflection (5°, 10°, 20° and 35°) and three different speeds (minimum, maximum, and the speed of 10 knots, which is approximately the middle between the minimum and the maximum speed of the selected ships) were simulated. During the simulations, all relevant data concerning the current motion of the ship and a graphical display of the performed simulation were recorded every 30 seconds.

## 6 Conclusion

This paper analyzes the ship track model in cases of an extraordinary event during navigation. The research was limited to the extraordinary event when a malfunction of the steering system occurs. The assumed extraordinary event affects the course and the speed of the ship thus defining the ship's motion and, in case of grounding, the extent of damage as well. For the selected extraordinary event, scenarios were defined for which a ship grounding model and a speed change model were developed.

For creating the ship grounding model, principles of ship's motion while turning were analyzed and conditions for the curve delineating the ship's trajectory were defined. The specified conditions are that the curve approximates the curve of a turning ship as close as possible, and that it has parameters (elements) that can be attributed to some characteristic property of the turning ship. Among all the analyzed curves, the Euler spiral/clothoid was identified as the curve that has the most similar properties to those of the curve of a turning ship.

The comparison of the curve of a turning ship and the clothoid led to the conclusion that in the first and the second phase, the clothoid approximates the curve of a turning ship very well, but in the third phase the principles of a circle should be applied. In order to meet the second condition, by modifying the parametric clothoid equation, a curve was obtained which approximated the curve of a turning ship very well. The obtained modified curve was tested on 60 scenarios conducted on a navigation simulator.

After the track model, a speed change model was also created. For purposes of this paper, a speed change model that can display speed change at any point of the curve of a turning ship when rudder deflection is constant and the engine stopped was designed. One of the important requirements concerning model development was defining the input parameter that can be attributed to a certain characteristic property of the ship during navigation at the moment of the occurrence of an extraordinary event. Initial ship speed was selected for this purpose.

The advantage of the model is that it does not take statistical data into account, but examines each scenario separately, allowing the later selection of the scenario that represents the most adverse event. The result of the most adverse event can be used to determine the extent of the ship grounding damage, i.e. grounding consequence.

The developed simulation models were applied to bulk carriers and tankers. Further research should be conducted to additionally develop these models by making data sets of motion and of other ship types, as well as of other extraordinary events. As an additional contribution to the quality of the track model, a systematic hydrodynamic analysis of ship motion should be performed, which would further verify the obtained ship track models.

A model can also be further developed with regard to its end user. For purposes of the state, a model can be developed for research concerning ship casualties and their consequences. The advantage of this kind of approach is proactive action, and the results obtained using the model would enable proper assessment of decisions that have to be made on a state level. In order to meet the needs of the Vessel Traffic Services, the model can be developed in the form of an algorithm that, based on the risk assessment, alerts/alarms the VTS operator about the possible danger, and the VTS operator can then act proactively and warn the vessel.

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