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APPLICATION OF THE PROBABILISTIC-FUZZY METHOD FOR ASSESSMENT OF A DANGEROUS SITUATION OF A SHIP MANOEUVRING IN A RESTRICTED AREA

ABSTRACT This article presents practical application of the probabilistic-fuzzy method for assessment of the safety of a ship manoeuvring in fairways. The method, based on the probabilistic risk analysis and elements of fuzzy logic, allows to account for a situation of threatened safety and a situation when a navigator intuitively thinks that the safety of manoeuvring ship is threatened. The probability of grounding of a ship manoeuvring in a fairway bend was determined. Then, with the use of experts' knowledge and tools of fuzzy logic the probability of a dangerous situation was determined. Two different approaches, discussed in Part 1, have been applied for the determination of the probability. The results were compared.

INTRODUCTION

Navigational safety of a ship manoeuvring in restricted areas such as fairways, harbour entrances, harbour basins, turning basins and others, is most frequently assessed by the quantitative analysis methods based on probabilistic methods.

One typical approach in such cases utilises data from simulated passages conducted by navigators. From the data one can estimate parameters of the density distribution function of the random variable of the distance from danger. The use of the density function makes it possible to determine the probability that a ship will move outside safe boundaries of the fairway, in which case a ship may run aground or strike a port structure. Such an event results in the system state being changed to safety failure and a navigational accident.

One shortcoming of the probabilistic method is that it is impossible to assess a situation when safety is threatened, that is a situation when a ship is manoeuvring close to the fairway boundary. This state, if no or inadequate measures are taken, can result in safety failure.

This article presents practical application of two different methods of determining the probability of a dangerous situation for a ship manoeuvring in a fairway bend. The results have been compared and extensively discussed in view of their practical application.

RESEARCH METHODOLOGY

The probabilistic-fuzzy method has been applied for assessment of ship manoeuvre safety. To this end both simulation research and expert studies have been performed.

SIMULATION RESEARCH

The research was carried out in a fairway bend, 150m wide at the bottom, with the radius of 600m (Fig. 1). The ship used for research was a loaded tanker with 40000 DWT capacity, length overall L=196m, beam B=28m and draft T=11m. The tanker was equipped with the right-hand turn propeller and a conventional rudder.

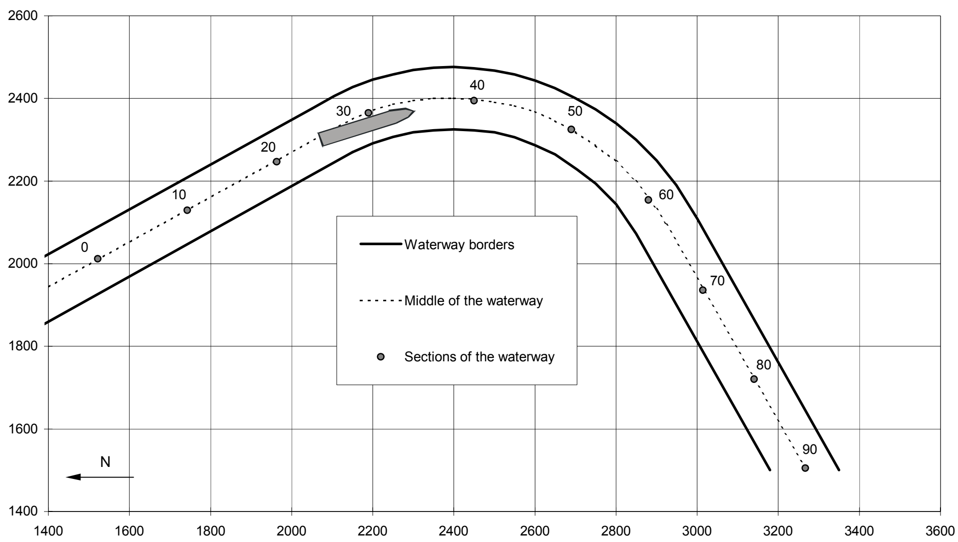

Fig. 1. The area of the bend divided into sections

In the studies a ship-handling simulator working in real time was used for the experiments. Ship's captains and pilots were invited to participate. The navigators were told to carry out a series of simulated passages, handling the ship through a part of the fairway. In the manoeuvres the rudder was mainly operated. The engine was only used in particular situations, and the ship was moving at full manoeuvring speed.

After a series of simulated trials, whose reliable size guaranteed a preset confidence level (30 trials), parameters of two density functions of the random variable were estimated: maximum distance of ship's points to the starboard and port side from the fairway centre line.

The fairway was divided into sections with limits running perpendicular to its centre line.

With the distance of 25 metres between sections, their total number amounted to n=90. Two random variables were identified in each section. It was assumed that the normal distribution well describes the distribution of ship's points to the starboard and port side of the fairway centre line, which had been confirmed by relevant statistical tests [5].

Figure 2 presents the estimated parameters of the mean and standard deviation of the distance of ship's points from the centre of the fairway for all the sections, their starboard and port sides.

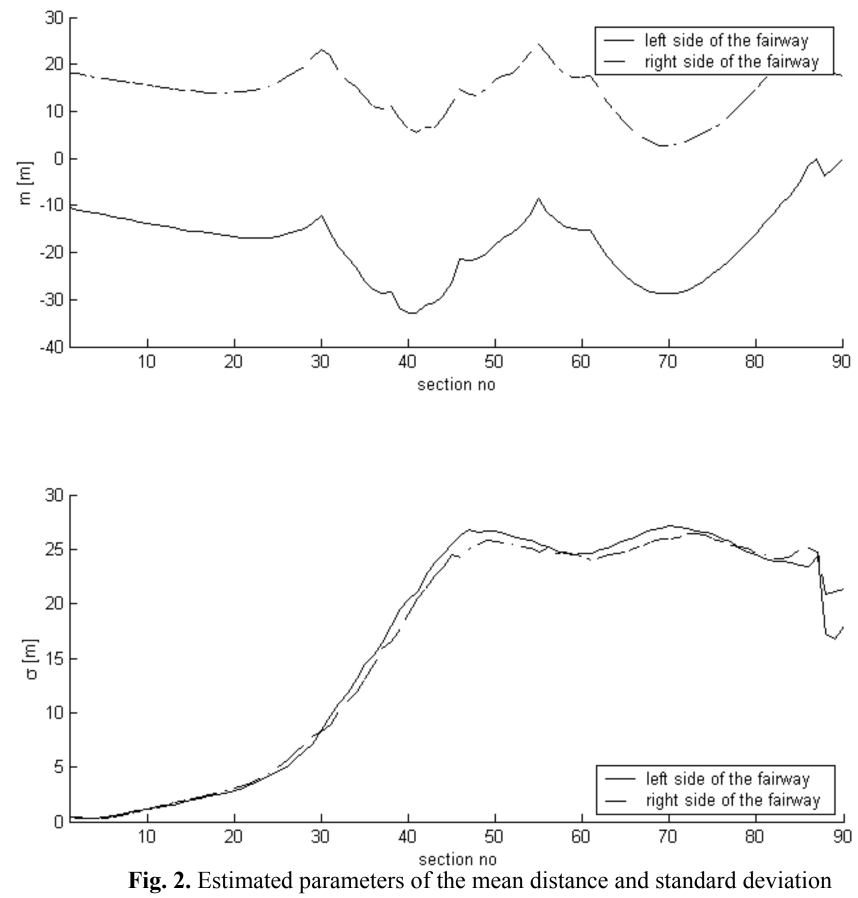

Fig. 2. Estimated parameters of the mean distance and standard deviation for all sections of the fairway. Fairway starboard and port sides.

Analysing the data shown in Figure 2 we can notice that the mean values of distances of ship's extreme points from the centre line of the fairway vary substantially, although the difference between the mean values needed for the determination of the so called mean swept path does not show significant changes along the whole length of the fairway. However, there is a characteristic shift of mean values to the starboard side close to section 30, and to the port side close to sections 40 and 70. This results from the character of particular manoeuvres in the bend, where in section 30 the ship moved taking a short cut due to an early turn, while in section 40 the ship moved to port as a consequence of its insufficient rate of turn; in section 70 the ship had problems with proper stopping of the turn.

An analysis of the size of standard deviations (Fig. 2) shows that on the port side of the fairway higher values occur. This means that the ship's swept path will move towards the port side and accident probability will be higher.

There is a characteristic increase in standard deviations in the region of sections 50 and 70, where vital manoeuvres within the bend are to be performed (second part of the turn, turn stopping and rudder put to starboard). The swept path of the manoeuvring ship in these sections widens; consequently, accident probability increases.

EXPERT STUDIES

The expert studies aimed at determining the membership function to a set 'dangerous situation' for the starboard and port sides of the fairway in each of the sections, $\mu_{Air}(x)$ and $\mu_{Ail}(x)$, respectively [3,4].

The basic criterion chosen for assessing a situation was the distance of the extreme port and starboard points of the water plane from the fairway centre line.

Experienced navigators who participated in the expert studies were those who had taken part in the simulated research.

Data from the questionnaires using the method of psychological scaling [7] was used to specify degrees of membership, found as dangerous by the navigators, to the set 'dangerous situation'.

The form of the function of membership to the set 'dangerous situation' for both fairway sides, as it is known in the literature [6], was modified:

$$\begin{cases} \mu_{Air}(\boldsymbol{x}) = 1 - \exp(-((\boldsymbol{x} - \boldsymbol{x_o}) / \boldsymbol{x}1)^2) & \textbf{\textit{for}} \quad \boldsymbol{x} > \boldsymbol{x}_0 \\ \mu_{Air}(\boldsymbol{x}) = 0 & \textbf{\textit{otherwise}} \end{cases} \tag{1}$$

$$\begin{cases} \mu_{Ail}(\boldsymbol{x}) = 1 - \exp(-((\boldsymbol{x} - \boldsymbol{x_o}) / \boldsymbol{x}1)^2) & \textbf{\textit{for}} \quad \boldsymbol{x} < \boldsymbol{x}_0 \\ \mu_{Ail}(\boldsymbol{x}) = 0 & \textbf{\textit{otherwise}} \end{cases} \tag{2}$$

then its parameters (x_0 and x_1) were estimated.

Examples of functions of membership to the set 'dangerous situation' for the port and starboard sides of the fairway in section 30 are illustrated in Figure 3.

On this basis the membership function parameters were estimated for the other sections of the examined fairway stretch. Their curves are shown in Figure 4.

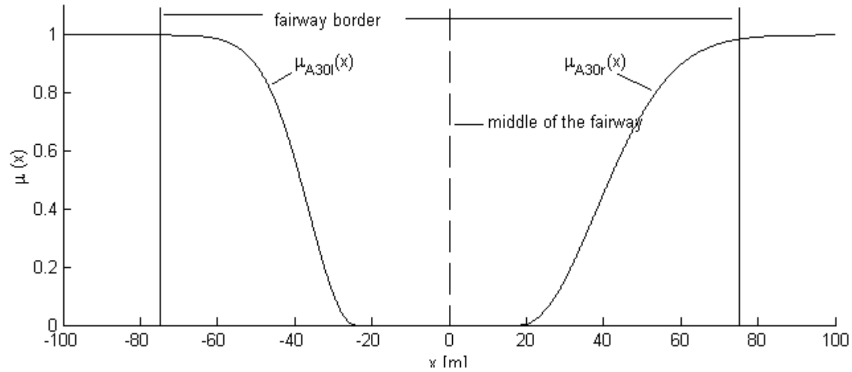

Fig. 3. Membership functions to the set 'dangerous situation' for the fairway port and starboard sides in section 30.

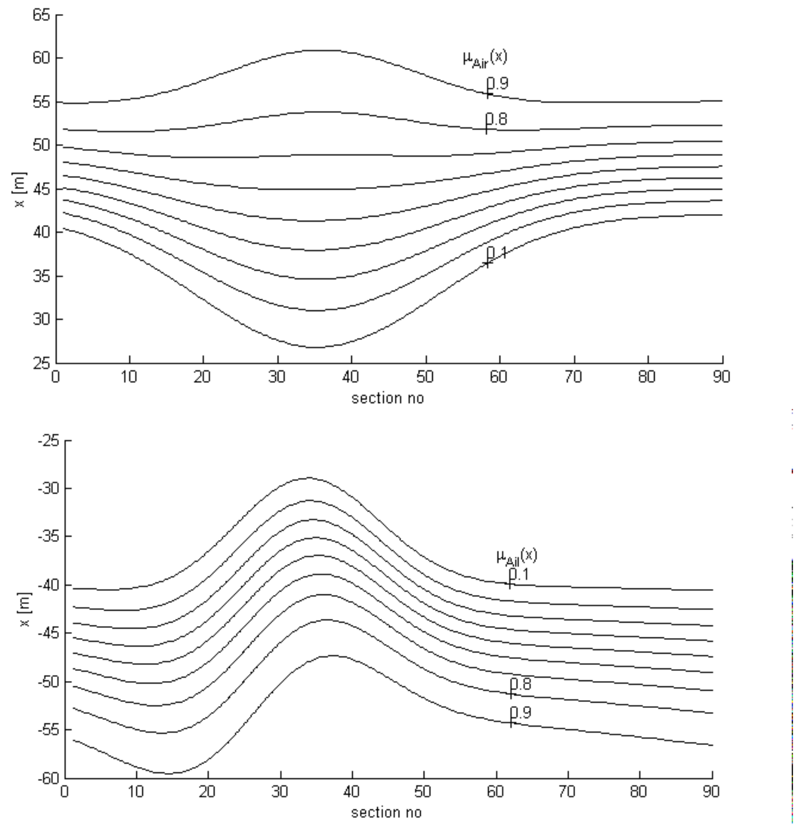

Fig. 4. A level line chart of the functions of membership to the set 'dangerous situation' for the starboard and port sides of the fairway.

If we analyse the data shown in Figure 4 we can notice essential differences in the navigators' assessment of the degree of danger depending on a section and the side of the fairway. On both starboard and port sides of the fairway the navigators-experts considered sections 30 to 40 as the most dangerous ones. It can be seen, however, that the port side was found the most dangerous, where the membership function amounts to 0.9 with the distance of only –50m from the fairway centre (more than 55m for the starboard side). This assessment is in compliance with the theory of manoeuvring. Although on the port side the channel effect facilitates a ship's turn, there exists a serious threat that a ship will strike the port side border of the fairway with its stern if its rate of turn is too high. Besides, we should take into account the fact that the navigators were supposed to pass through the fairway bend, which forced them to commence the manoeuvre in a strictly defined point. If the turning manoeuvre started to early or late, its safe performance may prove impossible.

The determination of the density function of the random variable x and the function of membership to the set 'dangerous situation' made it possible to calculate vectors of probability of dangerous situation occurrence. In the calculations both Zadeh's and Yager's approaches were applied.

THE RESULTS

ACCIDENT PROBABILITY

The previously estimated distribution parameters (mean and variance) were used for determining navigational safety failure.

In order to calculate the probability of an accident, the following equations are used:

$$p_{air} = \int_{x=d\max}^{+\infty} g_{ir}(x)d(x) \tag{3}$$

$$p_{ail} = \int_{x=-\infty}^{-d\max} g_{il}(x)d(x) \tag{4}$$

where:

- $g_{ir}(x)$ - ensity function of the random variable x of the maximum istance of ship's extreme points to the starboard side from ıe fairway centre line in the i-th section,
- $g_{il}(x)$ - ensity function of the random variable x of the maximum istance of ship's extreme points to the port side from the airway centre line in the i-th section,
- d_{max} - istance from the fairway centre to the fairway border (half f the fairway width).

When we consider separately the starboard and port border of the fairway, vectors of safety failure for the starboard *(P_{ar})* and port side *(P_{al})* of the fairway can be written as follows:

$$P_{ar} = [p_{a1r}, p_{a2r} \dots p_{anr}] \tag{5}$$

$$P_{al} = [p_{a1l}, p_{a2l} \dots p_{anl}] \tag{6}$$

where:

p_{air}	-	navigational safety failure in the i-th section of the starboard side of the fairway,
p_{ail}	-	navigational safety failure in the i-th section of the port side of the fairway,
n	-	number of sections

The results of calculations are given in Figure 5, which presents the probability of an accident for the entire fairway length on port and starboard sides.

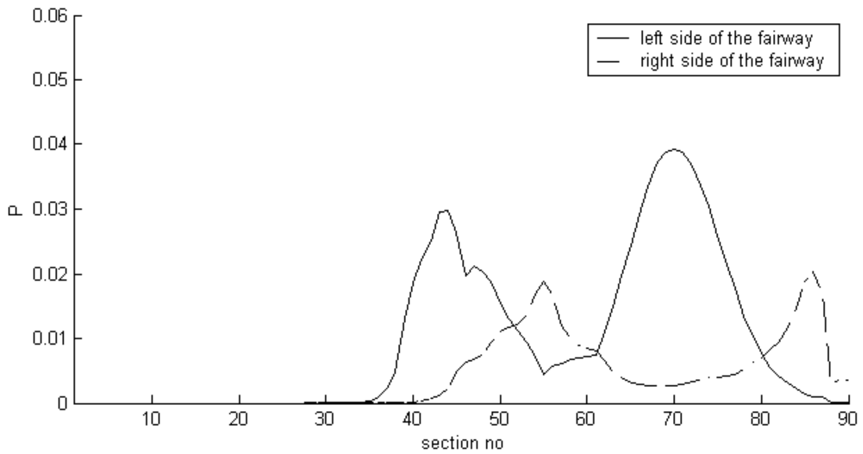

Fig. 5. Probability of an accident on the starboard and port side of the fairway.

The results illustrated in Figure 5 confirm earlier analyses. It can be seen that the probability that a ship will go aground is visibly higher on the fairway port side, while its highest values are found near sections 45 and 70. The highest probability of an accident on the starboard side exists in the region of sections 55 and 85.

The data presented in Figure 5 provide a conclusion that the navigators delayed the turn steering the ship too close to the port boundary of the fairway in the area of section 45. As a result, the course was corrected and, consequently, the ship was moving on the starboard side in the area of section 55. Furthermore, as a result of putting the helm to the other side, the ship dangerously moved to the port side in section 70.

PROBABILITY OF a DANGEROUS SITUATION

Zadeh's approach

Assuming that we know the density distributions of random variable x for, respectively, extreme starboard ($g_r(x)$) and port ($g_l(x)$) positions of ship water plane points as well as their corresponding functions of membership to sets 'dangerous situation' $\mu_{Ar}(x)$ and $\mu_{Al}(x)$, the probability that a dangerous situation will occur can be expressed by the equations [4, 7, 8]:

$$\mathrm{p_z(A_r)} = \int_{x=-\infty}^{\infty} \mu_{Ar}(x) g_r(x) d(x) \tag{7}$$

$$\mathrm{p_z(A_l)} = \int_{x=-\infty}^{\infty} \mu_{Al}(x) g_l(x) d(x) \tag{8}$$

Accepting the previously presented division of the fairway into sections, we can determine the probability of a dangerous situation for the starboard and port sides of the fairway in each section. As the starboard and port sides are considered separately, by analogy to relations (3) and (4), vectors of the probability that a dangerous situation will occur can be written in this form:

$$P_z(A_r) = [p_z(A_{1r}), p_z(A_{2r})... p_z(A_{nr})] \tag{9}$$

$$P_z(A_l) = [p_z(A_{1l}), p_z(A_{2l})... p_z(A_{nl})] \tag{10}$$

where:

- $p_z(A_{ir})$ - probability of a dangerous situation in i-th section of the starboard side of the fairway,
- $p_z(A_{il})$ - probability of a dangerous situation in i-th section of the port side of the fairway,
- n - number of sections

The values of probability of dangerous situation occurrence were defined for all the sections of the fairway on the port and starboard sides. The relevant data are presented in Figure 6.

Intuitively we may say that the probability of a dangerous situation $p_z(A)$ (Fig.6) is higher than the probability that a collision p_a occurs (Fig.5). This results from the fact that threatened safety situations were taken into account, which led to collision avoidance (for instance, thanks to a proper response of the navigator).

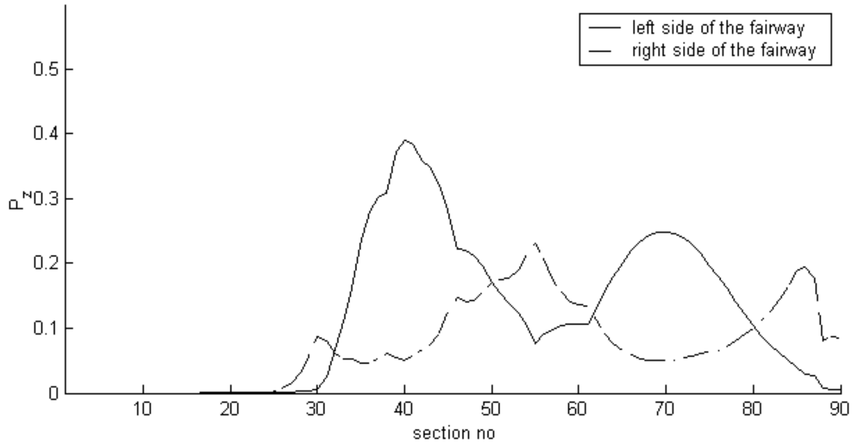

Fig. 6. The values of probability of dangerous situation occurrence for the fairway starboard and port sides (Zadeh's approach)

An analysis of data included in Figure 6 shows that the maximum values of both functions for identifying a dangerous situation are found in places of the fairway similar to those of the function representing the probability of an accident (Fig. 5.). It is interesting, however, that the first maximum for the port side of the fairway is located in the region of section 40 and is higher than the other maximums, which was not the case in functions describing accident probability (Fig. 5). Relatively high values of the probability of dangerous situation occurrence in this part of the fairway bend may result from the fact that possible danger is vital in terms of manoeuvring tactics. Each error done when a ship enters the bend, particularly a delayed turn, causes a dangerous situation in this part of the fairway. The navigator, being too close to the port side near section 40, is forced to increase the ship's rate of turn and speed up the manoeuvre. On the other hand, when the rudder goes more to starboard, there is a threat that the ship will hit its stern against the port side slope of the fairway.

The probability that a dangerous situation will occur on the port side is lower in the area of section 70 (Fig. 6) because the navigators found coming closer to the port side border as less dangerous in this part (ship leaves the bend and the section is straight) than in section 40 (curved section) in spite of the fact that the values of accident probability displayed a different trend (Fig. 5).

In this respect it is interesting to note the small value of the probability of a dangerous situation in section 30 on the port side as compared with the starboard side (Fig. 6). Among others, this results from the fact that, although the port side is safer in navigators' opinion, (the turn is facilitated by the turning moment of the channel effect), the ship was found more frequently on the starboard side due to a natural tendency of the navigator to accelerate and take a short-cut.

It is worth noting that, even if the navigator assessed a situation as dangerous, he is not able to manoeuvre the ship so as to avoid the danger. Consequently, in such cases the value of the probability of a dangerous situation will be high.

The presented method combines objective and subjective elements, resulting from navigators' knowledge and experience: the current situation (accident probability is the result of previous manoeuvres) and navigator's judgement concerning the degree of how dangerous the given situation is.

Yager's approach

With the assumption that we know the density distributions of random variable x for, respectively, extreme starboard $(g_r(x))$ and port $(g_l(x))$ positions of ship water plane points as well as their corresponding functions of membership to the sets 'dangerous situation' $\mu_{Ar}(x)$ and $\mu_{Al}(x)$, the probability that a dangerous situation will occur can be expressed by the equations [7]:

$$p_y(A_r) = \sum_{\alpha \in [0,1]} \alpha / p(A_{\alpha\, r}) \tag{11}$$

$$p_y(A_l) = \sum_{\alpha \in [0,1]} \alpha / p(A_{\alpha\, l}) \tag{12}$$

where:

$p_y(A_{\alpha\, r})$ – probability of a non-fuzzy event $A_{\alpha\, r}$

$p_y(A_{\alpha\, l})$ – probability of a non-fuzzy event $A_{\alpha\, l}$

Accepting the previously presented division of the fairway into sections we can determine the probability of a dangerous situation for the starboard and port sides of the fairway in each section.

To make the comparison of the results possible, only defuzzificated values of the probabilities of dangerous situations are presented.

As the starboard and port sides are considered separately, by analogy to relations (3) and (4), vectors of the probability of a dangerous situation can be written in this form:

$$P_y(A_r) = [p_y(A_{1r}), p_y(A_{2r}) \dots p_y(A_{nr})] \tag{13}$$

$$P_y(A_l) = [p_y(A_{1l}), p_y(A_{2l}) \dots p_y(A_{nl})] \tag{14}$$

when:

$p_y(A_{ir})$ - probability that a dangerous situation will occur in the i-th section of the starboard side of the fairway,

$p_y(A_{il})$ - probability that a dangerous situation will occur in the i-th section of the port side of the fairway,

n - number of sections.

In the next step comprising the whole fairway (all sections) the values of probabilities of dangerous situation occurring on the port and starboard sides were determined. The results are presented in Figure 7.

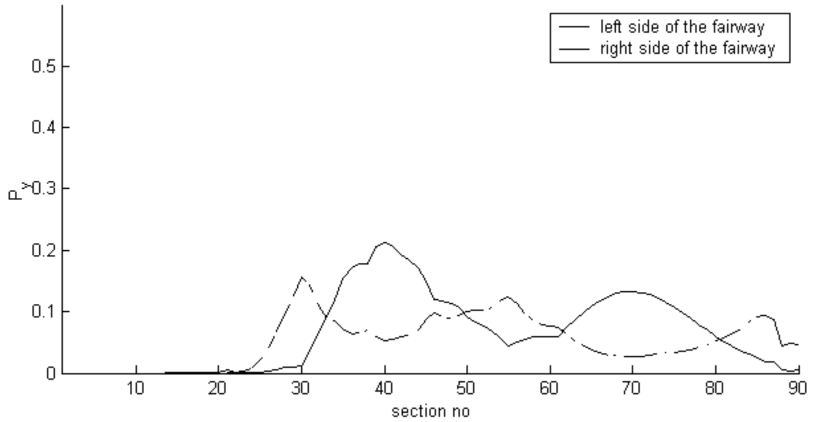

Fig. 7. Probability of a dangerous situation for the port and starboard sides of the fairway (Yager's approach)

The comparison of data presented in Figure 7 with the values of probability obtained by Zadeh's approach shows their high similarity in terms of value and function shape. The values of probability of dangerous situation occurrence in Zadeh's approach, however, are approximately twice higher depending on the section. The fact has to be further analysed, particularly because no similar examples of application are found in the world literature [1, 7, 8].

It should be noted that in Yager's approach, the difference between the maximums of the function describing the probability of a dangerous situation on the fairway port side in section 40 and 70 decreased as compared with Zadeh's approach.

CONCLUSIONS

The method herein described has a practical significance as it enables quantitative determination of the probability of dangerous situation occurrence. This article presents the application of the method for determining the probability of dangerous situations as they may occur in a fairway bend where a ship is manoeuvring. Such assessment of manoeuvre safety could then be further used in the process of optimisation of the fairway shapes in view of its safety or for the assessment of the safety of a conducted manoeuvre.

The approach described in this article has not been used in analyses so far. It combines a classical probabilistic method connected with a probability of a ship appearing in a particular position in the fairway with navigator's assessment of the degree of danger in a given place of the fairway. This assessment is described by the theory of fuzzy sets.

The article presents a practical interpretation of the method. Two different approaches to the assessment of probability of dangerous situation occurrence (Zadeh's and Yager's) show significant similarity of results; the differences should be further analysed.

In Yager's approach, from practical point of view it is important that the probability of dangerous situation occurrence is described with a fuzzy set. In this case, methods of fuzzy logic can be used in situations where other elements are also described with fuzzy sets, e.g. safe speed.

Regardless of the above remarks, both methods allow to determine real values of the probability of dangerous situation occurrence, which consequently provides a basis for analysis of navigational safety by conventional methods commonly used in practice.

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