The onboard expert measuring system for assessing the technogenic risk during towing operations based on the fuzzy logic

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Abstract. The article describes a method used to create an on-board measuring system to determine the degree of risk in towing operations using the mathematical apparatus of fuzzy logic. Based on the method of paired comparisons and transformations and using the interpolation method, membership functions of linguistic variables for determining the degree of risk were calculated. To eliminate the misperception of control commands in the tug in towing operations, the concordance component of risks was used. This method was used to assess the risk value for mooring with several operations. The on-board measuring system for risk assessment was developed. Its main component is a data bank containing factors that affect an assessment of the state and results of the fuzzy logic unit. The system can assist skippers in the decision-making process in shipboard operations. The fuzzy logic system was tested by interviewing maritime workers; the result proved the adequacy of this system.

1. Introduction
Operations with tugs refer to special cases of maritime practice associated with the risk of breaking the towing line [1]. According to GISIS IMO (Global Integrated Shipping Information System) statistics for 2015 – 2020, 1591 maritime incidents occurred, of which 60 ones accounted for by towing operations. According to the survey involving workers in the maritime industry, this system reflects incomplete information on maritime incidents. The Global Integrated Shipping Information System does not reflect incidents due to the absence of severe international consequences. Shipping companies are implementing the Risk Management Procedure in the Safety Management System (SMS) in accordance with the requirements of the International Safety Management Code (ISM Code). The risk management procedure provides for the creation of a group of trained specialists from ship's staff to assess the risk [2]. However, according to various sources, the culprit of the accident is the human element of the control system (80-90%) [3]. Therefore, there is a possibility of unprofessional risk assessment in ship operations by the command staff, due to the lack of experience in accidents and failures. On-board calculation of preliminary risks [4] for the purpose of preliminary safety assessment allows avoiding emergencies that may arise during towing operations [5].

One of the important components of risk assessment is an assessment of possible consequences. The tug "POSEIDON" approached the starboard side of the m / v "ANNENKOV" in the area of the
superstructure cutoff and received a towing rope from the side of the vessel. The POSEIDON tug operated in alternating modes to reverse. When the load increased to “full spinning”, the towing rope broke off in the area of the deck hawse of the ANNENKOV ferry and flew out onto the deck of the POSEIDON tugboat. Under the influence of wind of 12-14 m/s, the steam began to be demolished with a lag on the left side. The vessel had little backward inertia. When the danger of the ship's bow on the quay head had passed, the captain gave full speed forward, which led to the bulk of the ANNENKOV ferry on the bow of the LAUVER dredger, and then along the EKOLOG crew boat sliding to the stern.

In addition to the existing technogenic risk, there is a possibility of concordational misperception of the steering commands in tow. To reduce this factor, there are Master-Pilot information exchange (MPIX) checklists.

The technogenic risk assessment on board is carried out using special blanks filled out by a specialist before the operation. This approach refers to the “paper” security, which is widely discussed in the International Maritime Organization (IMO), and the assessment is guided by the experience of an expert with all individual gaps in qualifications and practice.

This work is intended to eliminate the above disadvantages. The study of automated calculation of the degree of risk on board in ship operations with tugs was based on the mathematical apparatus of fuzzy logic [6, 7].

2. Methods and materials

The use of the apparatus of fuzzy logic allows you to determine the risk under uncertainty. Mathematical tools allow you to build models that adequately reflect various aspects of uncertainty, with fuzzy initial information. This method involves the use of linguistic variables, which allow the use of qualitative characteristics expressed in natural language.

To describe the membership functions of the linguistic variables “probability”, “impact” and “degree of risk” the indirect method by T. Saati was used [8]. This method allows you to work in limited conditions, such as inadvertent distortion in information coming from experts. The method is based on the decomposition of the problem being solved by dividing it into simple elements. This division allows the pairwise comparison of elements, taking into account their impact on the overall performance, using rank measurements.

In calculating the final rank of elements, membership functions of elements describe elements or requirements for them.

Performing pairwise comparisons represents a matrix of the significance level of elements, determined by the following scale

- 1 - if the significance of elements is equal;
- 3 - if the significance of element 1 in comparison with element 2 is weak;
- 5 - if the significance of element 1 in comparison with element 2 is significant;
- 7 - if the significance of element 1 in comparison with element 2 is strong;
- 9 - if the significance of element 1 in comparison with element 2 is absolute;
- 2, 4, 6, 8 - intermediate comparative assessments: 2 - almost weak significance; 4 - almost significant; 6 - almost strong significance; 8 - almost absolute significance.

To determine the membership functions of linguistic variables, use the interpolation method, which is based on the nonlinear least squares method. The method is based on a least squares analysis form used to match a set of m observations with a model that is nonlinear by n unknown parameters.
Figure 1. The function model for the term of the "random" linguistic variable "probability"

The membership function coefficients were obtained with a confidence level of 95%:
- SSE: 0.02325
- R-square: 0.9666
- AdjustedR-square: 0.9333
- RMSE: 0.1078

The condition of the towing end is assessed according to the methodology of the Russian Maritime Register of Shipping [9, 10]. Regardless of the breaking force, natural and synthetic fiber towing ropes should not be used with a diameter less than 20 mm. Synthetic fiber ropes must be made of homogeneous approved materials (polypropylene, nylon, nylon, etc.).

The main determining factor for a special device on tugs is the bollard pull.

Table 1. Minimum breaking force (MBF) for the towing line

| BP, t | MBL, t | < 40 | 40 – 90 | >90 |
|-------|--------|------|---------|-----|
|       |        | 3,0\times BP | (3,8 – BP/50)BP | 2,0 \times BP |

It is allowed to determine the breaking force of the rope, F, kN by formula:

\[ F = cZFm n/z \]  

where
- \( c \) — the coefficient of using the strength of cables in the rope set by the standards or calculated as the ratio of breaking strength of the rope to the total breaking strength of all the cables in the rope;
- \( m \) — the number of tensile tested cables meeting the requirements of the standard;
- \( Fm \) - the greatest load preceding the destruction of the sample when testing one cable for tension, kN;
- \( n \) — the number of cables in a rope;
- \( z \) — the number of cables tested for tension, which is taken equal to 0.5 \( p \) for ropes with a circle of up to 80 mm, 0.3 \( p \) - with a circle from 80 to 115 mm and 0.1 \( p \) - with a circle of more than 115 mm.

The synthetic fiber rope shall be tested to determine the elongation at break.

The relative elongation of the rope under rupture \( \sigma_{av},\% \) is determined by formula:

\[ \sigma_{cp} = \frac{(l_p - l_0)}{l_0} \times 100 \]  

\( l_0 \) — initial length of the tested section of the rope sample, cm;
\( l_p \) — the length of the same section of the rope under a load equal to the breaking force of the rope specified in the standard, cm.

3. Risk model development method

Start developing the model by compiling membership functions of fuzzy linguistic variables. Build a model for the measuring system based on the current safety management system of a shipping company (SMS). The classification of probability (F) of damage from the SMS risk management procedure was described using five terms: “improbable” - it can happen only once, “random” - it can happen once in 5-10 years, “possible” - it can happen once in 5 years, “probable” - it can happen once a year, “frequent” - it can happen more than once a year. The entire range was taken as five equivalent ranges. To shorten the record, we used the following symbolic notation: N 1 - improbable, S 1 - random, V 1 - possible, VR 1 - probable, CH 1 - frequent (Fig. 1).

The shape and parameters of the membership function are assumed to be Gaussian, adopted on the basis of calculations that were made by the method of paired comparisons by T. Saaty. Gaussian membership functions are specified by two parameters: the minimum (maximum) value of the kernel of the fuzzy set [11]; the concentration coefficient of the left (right) part of the membership function. They also provide smooth, continuously differentiable response hypersurfaces of the fuzzy model. The range of the function is 1-5.

![Membership function plots](image)

**Figure 2.** The graph of the membership function for terms of the input linguistic variable “probability”

Describe the input parameter "impact" and the output parameter "degree of risk".

**Table 2.** Output rules for determining the degree of risk

| Impact       | Insignificant | Small | Significant | Critical | Catastrophic |
|--------------|---------------|-------|-------------|----------|--------------|
| Probability  |               |       |             |          |              |
| Improbable   | Very low      | Very low | Low         | Low      | Medium       |
| Random       | Very low      | Low   | Medium      | Medium   | High         |
| Possible     | Low           | Medium | Medium      | High     | High         |
| Probable     | Low           | Medium | High        | High     | Very high    |
| Frequent     | Medium        | High  | Very high   | Very high| Very high    |
The response surface allows you to analyze the fuzzy model as a whole and stepwise.

Figure 3. The surface of dependence of two input parameters "influence" and "impact"

4. The concordance component of risks of operations with tugs

The task was to assess concordance as an element of instability and risks when working with tugs. However, it is obvious that concordance can also be in the assessment of the condition of the towing ends, which is not always known to all controls. At the same time, it is quite clear that for effective control it is important to understand the previous moment, even more than the condition of the towing ends itself (except for the unlikely case when the towing ends are of little use).

Assume that there are several categories that the expert uses in evaluating parameters. Since it is not any load that leads to rupture, but at least an average tightness, it is logical that three levels can be distinguished - critical, high and medium. It is possible to distinguish three states of the cable - bad (it poses a small danger even at medium loads, medium and good). Since there is no need to determine specific values in this section, it is possible to represent the membership functions in the form of Gaussians with a hypothetical spread of the relative unit from 0 to 1.

If the centroid method is used,

$$A = \frac{\int_{1}^{U} a(V_{R-C_{c}})da}{\int_{1}^{U} (V_{R-C_{c}})da}$$  \hspace{1cm} (3)

where \(A\) – output result, \(a\) – variable, \((V_{R-C_{c}})\) – correlation of the section according to the rule; to assess the concordance in case of inconsistency of elements between experts in \(\Delta\), we will take the coefficient as the absolute difference:

$$K = \frac{\int_{1}^{U} a(V_{R-C_{c}})da}{\int_{1}^{U} (V_{R-C_{c}})da} - \frac{\int_{1}^{U} a(\Delta(V_{R-C_{c}}))d(a+\Delta)}{\int_{1}^{U} (V_{R-C_{c}})d(a+\Delta)}$$  \hspace{1cm} (4)

In total, for calculations with \(\Delta = 0.1a\) and two features containing three classification Gaussians, it was found that the maximum measurement error was 0.0413, while the probability of errors was higher than 0.01-0.36029. The mathematical expectation is 0.027334.

The probability of assessing the risk incorrectly when mooring with \(n\) operations can be calculated by formula:

$$P = \frac{(1-(1-P_{0.01}))^{n}}{2}$$  \hspace{1cm} (5)
The probability that the risk will be incorrectly estimated above 1% as a result of mooring with 10 teams is 0.384133.

5. Resulting system

Obviously, the advantages of the general system are matched by modernity - the larger the data bank, the better you can identify patterns.

The risk assessment measuring system can be presented as follows:

![Diagram](image)

**Figure 4.** The general view of the system

The knowledge base is filled in as follows: the factors influencing an assessment of the state, the results of the fuzzy logic block, the anonymous collection of results are entered into the knowledge base.

The measuring system can provide assistance to boatmasters.

However, there is a possibility to simplify the system. Obviously, the main concordance moments should be excluded. Thus, by adding elements of the end condition, as well as the central values of the force at the towing ends, it is possible to reduce the risk of incidents.

6. Validation

To check the measuring system and its relevance, a survey of workers in the maritime industry was conducted to determine the risk by the methods of shipping companies. The survey indicated the probability and impact, the respondent was required to independently determine the degree of risk.

Three control groups were identified: 1 - mixed, experienced and not experienced users.

The standard deviation of the indicators is shown in Fig. 5. The median value for each group was approximately the same as for the system under development: 0.61, 0.55 and 1.60, respectively.

At the same time, one cannot but admit the need for a more voluminous sample to be able to determine the root sources of errors in the human control element for towing operations. However, this task is beyond the scope of this study.

![Figure 5](image)
7. Conclusion
A system based on the mathematical apparatus of fuzzy logic, which measures and evaluates data, according to measures and an updated knowledge base, has been developed. The concordance component of the risk has been taken into account. The system is designed to work on board. The efficiency as well as the superiority of this system in the risk assessment over the existing procedures have been described.

Further modification of the system can be made for towing in unmanned navigation, but this requires more data - these operations are unique in maritime practice.

This study can serve as a basis for the research in understanding the root causes of an incorrect expert assessment of the degree of risk by the procedures of safety management systems of shipping companies.

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