Ship control optimization in heavy weather conditions

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Abstract The task of ship ocean routing efficiency improvement was defined. This is done by optimizing the ship voyage planning and on-scene control procedures. Optimization goal is reached for the account of improvement of methods for ship dynamics computation and operative route adjustment. To reach the prescribed goal the appropriate set of problems was defined. To reach the solution of the first problem, which is devoted to development of ship motion mathematical model, two models were developed: basic linear model – for calculation of motion parameters in irregular seas in relatively small oscillation range, and non-linear model – for calculation of complicated rolling regimes: simple and parametric resonances, reduce of stability in waves.

Second task is devoted to the development of specific ship state in waves parameters computation techniques, particularly: definition of unsafe rolling zones, intensity of slamming, green water and propeller immersion, speed reduction due to wind and waves.

The result of third task solution is came as the complex two-level multi-criteria ship state assessment system, modeled on the basis of fuzzy logic theory. For the formation of prescribed system the risk assessment concept was applied. All that gave the possibility to obtain the integral ship state assessment in form of generic risk level from heterogeneous data.

The fourth task is devoted to optimal control regime and transoceanic route search method. The search is performed by genetic algorithms method. As objective function in first case the integral assessment of safety and economical efficiency of selected control regime is used. In second case for this purpose the minimum of additional voyage costs, caused by environmental influence with preliminary calculated minimal costs in calm water is used.

The solution of the above mentioned tasks allowed the developing of a complex method for searching the optimal route and control regimes in heavy weather conditions.

For the approval of correctness and efficiency of results proposed in this work, corresponding algorithms and programs were developed. Check computations on the developed programs and models of voyage planning and on-scene control in heavy weather allowed to confirm the reliability and efficiency of obtained results.

Keyword: *ship, waves, control regime, voyage planning.*

1. Introduction

The success of ship sea passage greatly depends on the weather conditions. If the ship is going to pass the area of storm or due to prevalent circumstances she's found herself in adverse weather conditions, a navigator gets a task to find optimal from points of safety and efficiency ship's speed and heading.

Relatively high accident rate and weak navigator's informational support of decision making in waves stipulate the necessity of development of the automated methods aimed to find an optimal ship control regime in waves.

2. Risk assessment

The first stage in choosing the ship control regime, from our opinion, should be assessment of the risks conducted with her activity in heavy weather conditions. Mathematically the risk level can be defined as product of probability of hazardous occurrence P and it consequence A.

In our case we define *P* as the probability of reaching defined dynamical motion parameters that may lead to the series of negative consequences, conducted with ship's operation in storm.

Making the risk assessment of ship operation in heavy weather conditions one can define the situations connected with damages to hull structure, ship's systems and machinery and the situations arising due to violations of cargo handling technology.

For instance, the achievement of defined high amplitudes of roll may lead to the series of situations with different levels of consequences, such as shifting or loss of cargo, flooding of ship's compartments, capsizing.

Therefore, by defining function *R = f(P,A)*, we can build the corresponding *risk matrix* (fig. 1).

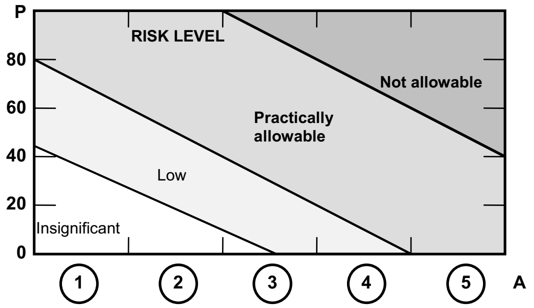

Fig. 1 Risk matrix

Let's highlight next risk levels: insignificant, low, practically allowable and not allowable. The risk management should cover such measures which allow to vary the probability of definite event or to reduce the degree of its consequence. When solving the problem of optimal ship control regime selection in heavy seas we assume the degree of consequence as constant. From the other hand by altering ship control parameters operator can affect the probability of reaching such ship motion parameters that lay beyond the limits of practically allowable risk. In this case the risk level can be given as

$$R = f\left(P_1, P_2, ..., P_n\right), \qquad (1)$$

where $P_1, P_2, ..., P_n$ - probabilities of reaching the ship motion parameters, that may lead to definite hazardous occurrence.

3. Seaworthiness criterions

To perform the risk assessment and to find the optimal control regime in given weather conditions it's necessary to define the criteria that allow to evaluate it efficiency, in other words to define the safe and economical control regime.

During development of corresponding criteria following factors should be taken into account:

- frequency and force of slamming;
- frequency of green water;
- motion amplitudes;
- hull stresses;
- propeller racing;
- accelerations in various ship points;
- forced and controlled speed redaction;
- deviation from planned route.

First six factors define safety of ship operation, other two – the efficiency. The table of general operability limiting criteria for ships in waves are given down below (*Lipis, 1972; Stevens, 2002)*:

Criterion	Cruikshank & Landsberg (USA)	Tasaki et al. (Japan)	NORDFORSK, 87 (Europe)	NATO STANAG 4154 (USA)
RMS of vertical accelerations on forward perpendicular	0.25 g	0.8 g / P = 10^{-3}	0.275g (L_{pp} < 100 м) 0.05g (L_{pp} > 300 м)	-
RMS of vertical accelerations on the bridge	0.2 g	-	0.15g	0.2g
RMS of transverse accelerations on the bridge	-	0.6 g / P = 10^{-3}	0.12g	0.1g
RMS of roll motions	15°	25°/ P = 10^{-3}	6°	4°
RMS of pitch motions	-	-	-	1.5°
Probability of slamming	0.06	0.01	0.03 (L_{pp} < 100 м) 0.01 (L_{pp} > 300 м)	-
Probability of deck wetness	0.07	0.01	0.05	-
Probability of propeller racing	0.25	0.1	-	-

*The significant motion amplitudes ($X_{1/3}$) can be obtained by doubling the corresponding RMS (root mean square value).

Table 1. General operability limiting criteria for ships

In table 1 the operability criteria for wide spectra of ships are given. However criteria of NORDFORSK and NATO STANAG appear to be too strict, and in series cases when ship proceeds through a heavy storm the motion parameters may exceed these criteria.

According to inquiry of 100 management level navigators (captains and chief mates) passing the Ship Handling course in Training & Certifying Centre of Seafarers of Odessa National Maritime Academy (TCCS ONMA) following operability criteria were obtained:

	Roll motion amplitude, °	Slamming, intensity per hour	Deck wetness, intensity per hour	Speed reduction, %	Deviation from course, °
Small	< 7	< 5	< 5	< 13	< 20
Not dangerous	< 14	< 11	< 10	< 24	< 38
Substantial	< 23	< 19	< 20	< 46	> 40
Dangerous	> 26	> 23	> 23	> 58	-

*The average values of inquiry data are given.
** Example: slamming probability with period of pitch 5 sec and intensity 20 times/hour: **0.028**

Table 2. Management level navigators inquiry data

In table 2 the empirical values of ship operability criteria are given. Usage of last gives possibility to perform more detailed, supported by personal seagoing experience of navigators, assessment of ship state in waves.

It should be noted that risk assessment by only threshold values, defined for the series of criteria is ineffective. Therefore in this case we suggest to apply not two-valued state function, but numerical or linguistic function, defined in range between two extreme values: «0» - «1», «best» - «not allowable» (minimal – maximal risk level).

In the capacity of limiting value in each case we take the *generalized safety criterion* –marginal risk level at which the ship operation is safe in defined conditions.

4. Fuzzy logic assessment system

To implement above mentioned suggestion on the basis of fuzzy logic multicriterion seakeeping efficiency assessment system was built (fig. 2). As the data used to generate

corresponding fuzzy inference subsystems (FIS) existing international ship operability criteria and expert inquiry results were taken.
The seakeeping efficiency assessment algorithm works in the following way. Parameters, taken as the system input, passing the FIS structure of the 1st level. As the result on the output we receive series of rates on each criterion (for instance, roll amplitude: “small”, “substantial” or “dangerous”). Rates may be given either as linguistic terms or in defined numerical range.

In course of definition system’s membership functions (MF) it suggested to form boundary conditions on the basis of existing international operability criteria, and MF’s intermediate values by approximation of preliminary transformed expert inquiry data.
After that obtained rates pass the FIS of the 2nd level, on the output of which the general assessment on the set of conditions is obtained (risk level, efficiency). The estimation of the objective function is done on the last stage by transformation of local safety and economy rates through the FIS of the 3rd level.

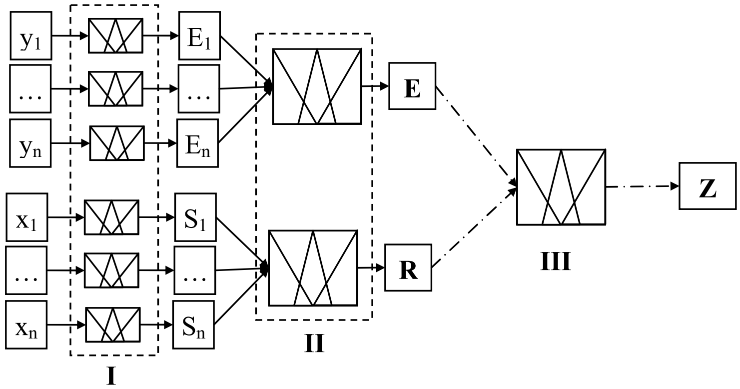

Fig. 2 Multicriterion seakeeping efficiency assessment system

$x_1 \dots x_n$ – motion parameters, $S_1 \dots S_n$ – corresponding rates, $y_1 \dots y_n$ – economical parameters, $E_1 \dots E_n$ – corresponding rates, R – risk level, E – level of economic efficiency, Z – objective function.

The FIS subsystem development process can be divided on the next stages:

STAGE 1. Definition of membership functions μ of deterministic input x and output y variables to fuzzy linguistic sets A and B. This includes formation of simple statements in antecedents and rules conclusions, and statistical membership estimation of defined parameters to the corresponding linguistic terms.

STAGE 2. The fuzzy rules Π database formation on the basis of fuzzy linguistic ensembles A and B. On this stage is important to provide completeness and consistency of the database.

STAGE 3. Definition of the fuzzy inference algorithm, such as algorithms of Mamdani, Takagi-Sugeno, Tsukamoto, Larsen and others.

In our case all three FIS modules appear as MISO (multi-input-single-output) structures and built on the basis of Mamdani fuzzy inference algorithm (*Borisov et al., 2007)*.
More detailed membership functions and rules databases formation process is described in *Pipchenko (2010).*

5. Decision evaluation

Research results obtained in woks *(Pipchenko, Zhukov, 2008; Nechaev, Pipchenko, Sizov 2009; Pipchenko, 2010)*, and arrangement of above described ship seaworthiness assessment system allowed to develop the ship optimal control regime selection method for adverse weather conditions (fig. 3).
The method can be described in following way. Before the voyage with known load condition ship motion parameters X are calculated in all range of wavelength’s, ship speeds and courses

(λ,U,μ). By the actual wave spectra S_ς and X the diagrams of motion in irregular waves $\tilde{X}$ should be obtained. For defined motion parameters *(U,μ)* the objective function *Z* (level of efficiency reasonable risk) should be defined. Here optimization goal is to find minimal value of Z in prescribed weather conditions that corresponds to the minimal possible risk and deviation from the planned route. It's suggested to perform the search of optimal control regime by genetic algorithms (GA) method.

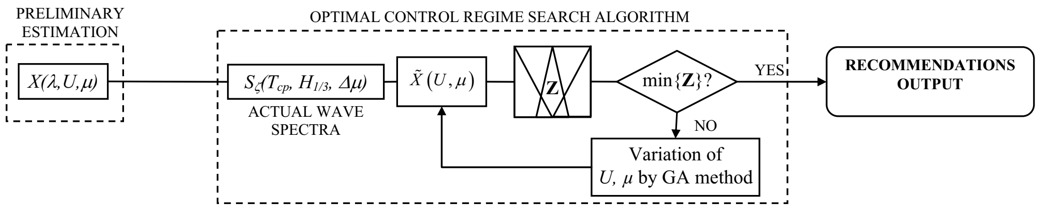

Fig. 3 The flowchart of optimal ship control regime selection method for adverse weather conditions

On the fig. 4 the working example of suggested algorithm is given. Container carrier proceeds in following waves (wave is encountering from the starboard aft quarter, 135°) undergoing significant rolling motions with amplitude up to 36°. Such ship dynamic state is assessed by the system as *not allowable*. From navigators inquiry data determined that there two classical solutions of this task. First is to turn into the head waves and to slow down depending on slamming and green water intensity. Second is to come into clearly following waves (μ = 180°) and increase speed. The machine decision in this case is to put the wave on the course angle of 160° and increase speed up to 25 knots. By analyzing storm diagram on fig. 2 it can be concluded that such solution of this task is the most efficient as with small course alteration and speed increase ship will encounter much smaller rolling motion (amplitude 10°).

6. Conclusion

In this article the multilevel ship seaworthiness assessment system built on the basis of fuzzy logic theory and risk assessment concept is represented.

The advantages of the developed system are: multi-level open structure, ability to adapt, usage of navigator's practical experience, convenience of results interpretation.

On the basis of obtained system the ship optimal control regime in storm search method was developed, implementation of which may significantly simplify the process of selection of safe and efficient ship control regime in adverse weather conditions.

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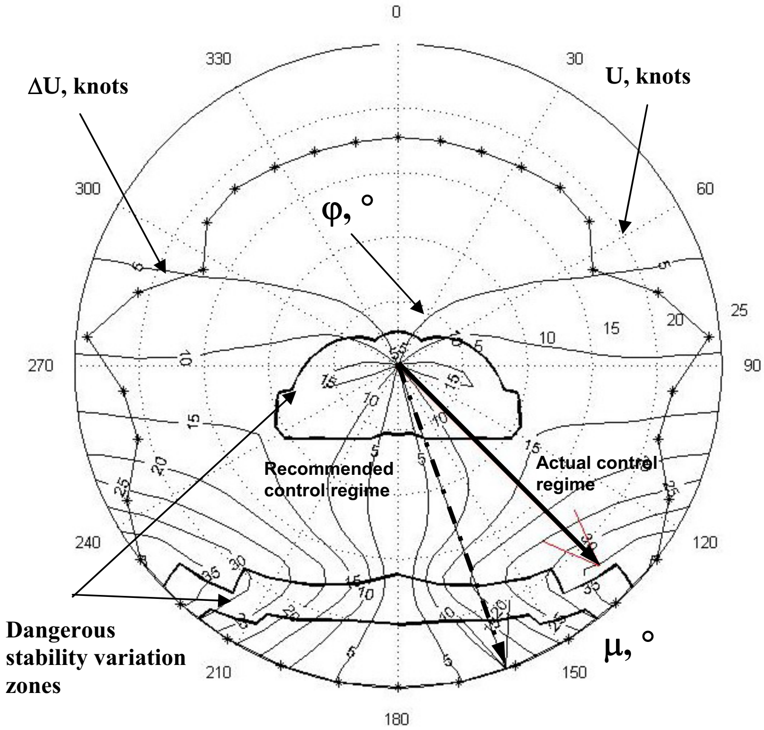

Ship state assessment in waves form

Vessel parameters: L = 200 m, B = 30 m, GM = 1.0 m; **Wave parameters**: $H_{1/3}$ = 10 m, Tcp = 11.5 s				
Control regime Actual / Recommended				
Wave encounter angle		Ship speed (U_P = 25 knots)		
135 / 160°		22 / 25 knots		
Operability state assessment				
Significant rolling amplitude	Green water: Probability// Intensity	Slaming Probability// Intensity	Speed reduction	Deviation from course
36 / 10°	0// 0 times/hour	0// 0 times/hour	**0 knots**	0/25°
Not allowable/Not dangerous	**NA**	**NA**	**NA**	**Moderate**
Is the vessel in resonance zone?		No		
Risk level		0.88/0.1	Not allowable / Allowable	
Economic efficiency assessment		0.26/0.29	Economical / Economical	
General assessment		**0.88/0.33**	**Not allowable / Good**	

Fig. 4 Optimal ship control regime selection algorithm performance illustration