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Optimization of Routing Considering Uncertainties

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Abstract: A route optimization methodology in the frame of an onboard decision support/guidance system for the ship's master has been developed and is presented in this paper. The method aims at the minimization of the fuel voyage cost and the risks related to the ship's seakeeping performance expected to be within acceptable limits of voyage duration. Parts of this methodology were implemented by interfacing alternative probability assessment methods, such as Monte Carlo, first order reliability method (FORM) and second order reliability method (SORM), and a 3-D seakeeping code, including a software tool for the calculation of the added resistance in waves of NTUA-SDL. The entire system was integrated within the probabilistic analysis software PROBAN. Two of the main modules for the calculation of added resistance and the probabilistic assessment for the considered seakeeping hazards with respect to exceedance levels of predefined threshold values are herein elaborated and validation studies proved their efficiency in view of their implementation into an on-board optimization system.

Keywords: routing system; operational risk assessment; multi-objective optimization; epistemic and aleatory uncertainties
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1 Introduction

Ships should be designed to withstand extreme weather conditions during their voyage within broadly defined limits. Independently of design measures to improve a ship's safety ('risk-based design', Papanikolaou, 2009), the safe operation of a ship is the responsibility of the ship's master ('risk-based operation'). The captain and his crew may be well trained to recognize dangerous situations and take measures to avoid them. Their decisions are in general based on their experience and the available information about the ship's and environmental condition. Unfortunately, information about the weather and its likely impact on a ship's performance is quite limited and uncertain. Thus, the captain needs to assess the consequences of his decisions based on the available information presented on the various displays and other equipment at the navigational bridge as well as on his previous experience.

In recent years ship routing and decision support systems have become important tools in relation to the safety and the optimization of the economy of sea transportation. Safety of the ship, crew, and cargo (and passengers, as applicable), minimization of fuel consumption and the release of toxic exhaust gases, and time restrictions for the delivery of the cargo form a complex multi-objective optimization problem with opposing targets.

The assessment of seakeeping events, of a ship's structural integrity and calculations of added resistance and powering in waves is a necessary ingredient of such decision support systems which are employed for the evaluation of the appropriate route and ship speed. In the deterministic seakeeping problem the above calculations and assessments are based on specific ship inherent and environmental data and assumptions. However, in realistic conditions each parameter of the seakeeping problem, even sensitive to the seakeeping ship inherent data, such as the GM and radius of gyration, is related to a degree of uncertainty (epistemic uncertainties), whereas other parameters, such as environmental data (wind, currents, and waves), are inherently random (and of aleatory uncertainty). The above uncertain parameters and random variables define an intricate probabilistic problem, the solution of which is, in addition to its complexity, very time consuming for onboard decision applications.

In this paper, which is based on relevant research conducted by the authors within the EU funded, FP6 project ADOPT (2005-2008) of the European Commission (Contract No FP6-TST4-CT-2005-516359), the methodology of an onboard decision support route optimization system for the evaluation of the seakeeping parameters and the conditions affecting the ship's navigation is introduced.

Having such a system installed onboard, alternative navigational conditions may be evaluated online and the optimum route control option can be given to the master for the minimization of the emerging risk and the minimization of fuel cost within an acceptable route time frame.

The modules of the system for the calculation of added resistance in waves and the estimation of the probabilities of exceedence for various seakeeping events are herein

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elaborated, and results of their application to the operation of sample ships are presented and discussed.

2 Route optimization methodology

A modern route optimization decision support system should focus on optimizing the safety of the ship and the reduction of the journey cost by sensing the environment for actual weather and environmental data and predicting the ship motions accordingly while ensuring optimal operational performance; it relies on a computer based decision support platform to be used by the ship's master in ship operation.

Such a system must provide adequate information and guidance by offering an evaluation of consequences, giving insight in the uncertainty of the environmental parameters (wind, waves, and currents), the ship's loading condition, the heading against the main wave direction and routing, and of other data by use of appropriate deterministic or probabilistic models as applicable.

2.1 System structure

The basic structure of the route optimization system methodology of NTUA-SDL is introduced in this paper and sketched in Fig.1. The system is comprised of four main modules, namely:

- The added resistance module for the calculations of the added resistance in waves,
- The seakeeping hazards module for the calculations of seakeeping events affecting the structural integrity of the ship and the safety of the crew and the cargo,
- The risk calculation module which on the basis of the probability of emergence of an event calculates the corresponding risk and consequences
- The route evaluation module for the evaluation of the alternative navigation conditions based on the user's criteria.

The main inputs of the system should be the ship's main characteristics, namely the ship's geometry and weight distribution, propulsion system characteristics, resistance in calm water and weather data for the specified route as waves, winds, and currents. The weather data should be at best available continuously onboard, to allow predictions in a 3-hour window.

The output should be the information given to the master for selecting the optimum route that will minimize the emerging risks due to weather, the fuel cost, and carbon dioxide (CO_2) emissions (or EEDI index), within an acceptable route time frame.

The ship's operational data (speed and heading to the sea) should be utilized as decision parameters for producing different navigation conditions for evaluation.

For the evaluation of the alternative routes, cost criteria relative to the reduction of the fuel and the cost of the delay should be used. Risk can be assessed depending on its category which can be classified as follows:

- Economic risk (damage to ship structure, equipment, and cargo, including total loss of cargo and ship, loss of reputation).
- Safety of people (loss of life, injuries, and health).
- Risk to the maritime environment (especially oil spillage for damaged tanker ships).

The first of the above categories can be expressed in monetary units and be assessed by cost criteria while the other two categories may be treated by other risk criteria and restrictions, though eventually all consequences may be summed-up and assessed in monetary terms. The risk evaluation with respect to the optimum route is governed by several constraint parameters related to ship's stability, structural integrity, specified loading conditions, and characteristic parameters related to the specified voyage (route scenario).

2.2 Main software modules and tools

The calculation of ship responses, including the added resistance and powering in waves, the probabilistic analysis of the seakeeping hazards, and the optimization procedure should be conducted by state-of-the art computational tools, allowing the execution of calculations by an onboard computer. The main software tools employed in the route optimization system of NTUA-SDL are:

- Newdrift, developed by Papanikolaou (1989), is a 6 DOF, 3-D panel code for the seakeeping and wave induced load analysis of ships and arbitrarily shaped floating structures, including multi-body arrangements. The code enables the evaluation of 6 DOF first -and quasi second - order motions and wave-induced loads, including drift deviations, forces, and moments and is applicable to arbitrarily shaped 3-D floating or submerged bodies (such as ships, floating structures, or underwater vehicles), operating at zero or nonzero forward speed, finite or infinite water depth, and being excited by sinusoidal linear waves, arbitrary frequency, or headings. The consideration of natural seaway excitation is enabled through a spectral analysis postprocessor SPECTRA, given the incident spectral characteristics.
- Added Resistance Code, developed by Liu *et al.* (2011) calculates Added Resistance Response Functions in regular seas by Maruo's far-field theory and uses a semi-analytical correction for short wave lengths. NEWDRIFT or a new Time Domain Green Function Method developed in the PhD thesis of Liu (2011) may be used to calculate the velocity potential and the linear ship responses.
- PROBAN, developed by DNV in 1989 (Det Norske Veritas, 2003), is a tool for general purpose probabilistic analysis. The main objective of PROBAN is to provide a variety of methods aimed at different types of probabilistic

analysis. This includes probability analysis, first passage probability analysis, and crossing rate analysis. It can deal with a broad class of probabilistic and statistical problems. PROBAN allows efficient modeling of random variables and events.

- ModeFRONTIER developed by ES.TEC.O in 1999 is a multi-objective optimization and design environment that features the most recent optimization techniques as mono-objective optimization algorithms (SIMPLEX algorithms, Gradient-based methods), multi-objective algorithms (MOGA), optimization algorithms and robust design tools, statistical analysis tools, design of experiments (DOE), and data-mining tools.

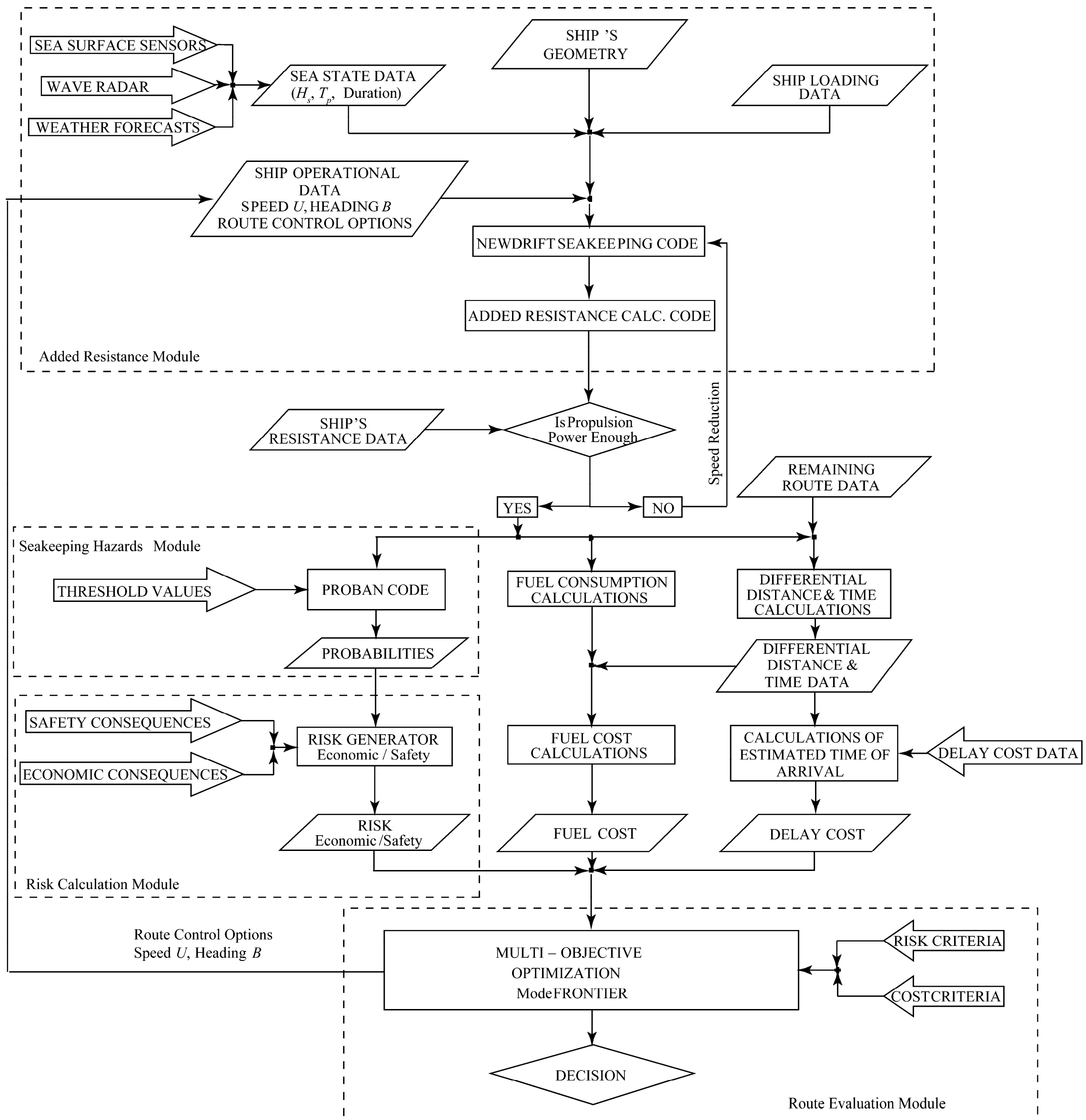

Fig.1 Structure of route optimization system of NTUA-SDL

3 Added resistance calculations

In order to address the reduction of the fuel cost and the CO_2 emissions within a route optimization system, it is important to dispose accurate calculations of the ship's added resistance and powering in waves. The added resistance in waves is the increase of a ship's calm water resistance that is caused by the encountered waves. Calculations of the added resistance can be used as a correction to the calm water resistance to predict the total resistance of a ship in a seaway. A ship may experience in common seaways a 20%–40% resistance and powering increase, while its speed of advance is reduced, for which the added resistance is the main reason. Thus, being able to predict accurately the added resistance in waves is a vital part of a route optimization system; it is noted that this aspect is greatly neglected in many widely used commercial route assistance systems, which employ outdated theoretical or simple semi-empirical approaches to the calculation of the increased powering in waves.

3.1 Added resistance in regular seas

The Added Resistance Code of NTUA-SDL was introduced in 2009 (Liu *et al*., 2011). This code calculates Added Resistance Response Functions in regular seas by using Maruo's far-field approach theory (Maruo, 1963) and the Kochin functions approach and uses a correction formula (Kuroda *et al*., 2008) for short wave lengths. The velocity potential and the linear ship responses for the calculation of added resistance can be given by the seakeeping code NEWDRIFT (Papanikolaou, 1989) or the new hybrid time domain Green function method developed in Liu (2011). The results of this code were compared with those of other well-established authors and experimental data and a reasonable agreement was observed, suggesting that the implemented procedure appears to be a reliable and robust method for the routine prediction of the added resistance of a ship in waves.

For this module of the optimization methodology, this code and the NEWDRIFT code were interfaced and the resulting Response Functions were used for the calculations of the added resistance in irregular seas.

3.2 Added resistance in irregular seas

The added resistance in irregular waves, expressed by a sea spectrum, may be expressed by superposition of the ship responses of the constituent regular waves, namely:

$$\overline{R}_{AW} = 2\int_0^\infty R(\omega)\cdot S_\zeta(\omega)\cdot \mathrm{d}\omega \tag{1}$$

$$R(\omega) = \frac{R_{AW}(\omega)}{\zeta_a^2} \tag{2}$$

where $S_\zeta(\omega)$ is the wave energy spectrum, R_{AW} the added-resistance response function in regular waves, and ζ_α the regular wave amplitude.

3.3 Application of the added resistance module

A validation study for the added resistance of an AFRAMAX oil tanker design is herein discussed for sea state conditions in the Caribbean Sea (Sames *et al*., 2011). The main characteristics of the ship are: L_{BP}=242.0 m, B=44.0 m, T=13.7 m, Vs=15.5 kn, engine power is 13560kW (at 100% MCR)

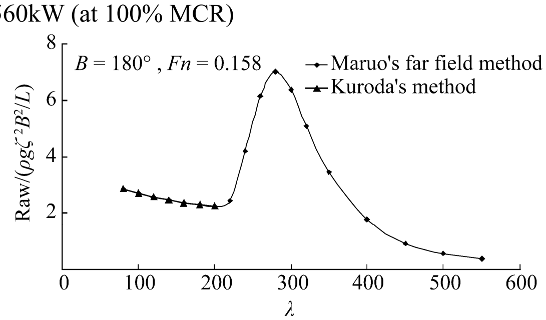

Fig.2 Added resistance response functions

For the modeling of the Caribbean Sea conditions a Bretschneider spectrum was used. In Fig.2 the added resistance response functions for a speed of 16 kn are shown.

Tables 1–3 illustrate the modeled Caribbean Sea wave scatter. Lightly shaded areas represent sea states for which the calculated added resistance is less than the values (within the margins) of 95%, 88%, and 84% confidence curves, shown in Fig.3 and 4. Darker shaded cells in Tables 1–3 indicate the marginal sea state for which the added resistance calculations were performed and which divide the wave scatter tables into safe (shaded) and unsafe weather conditions.

Added resistance results compared to the calm water resistance are shown in Fig.3. In 84% of the probable sea states in the area of operation, the ship sustains an added resistance increase of up to 19% compared to the calm water resistance, while there are 11% of probable seaways with a resistance increase from 19% to 35% and a 5% added resistance increase of more than 35%.

The study ship, with an embedded sea margin of 10%, can maintain her speed at 84% of the likely seaways in the specified area by operating at 85% of the Maximum Continuous Rating as Fig.4 illustrates. With the selected main engine of 13 560 kW brake power, the ship can operate at the specified area with a confidence of 95%, by increasing up to about 98% of the MCR or by having a minor speed loss of 0.5 kn.

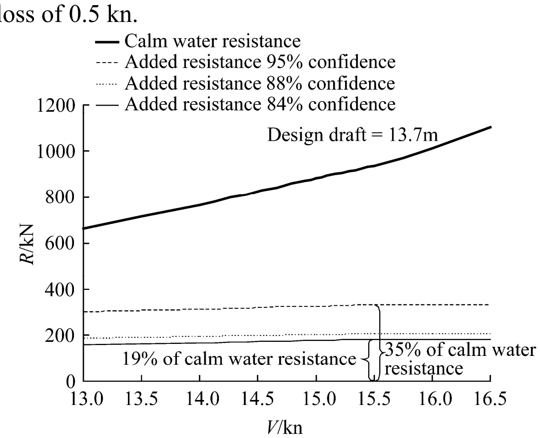

Fig.3 Added resistance results with different percentages of confidence

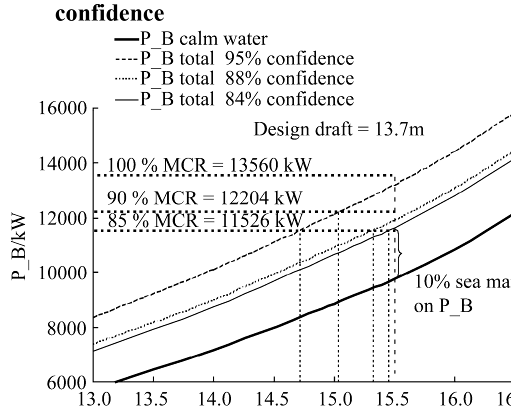

Fig.4 Brake Power results with different percentages of confidence

Table 1 Caribbean Sea wave scatter areas with 95% confidence for added resistance calculations

$H_s \backslash T_z$	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	Row sum
0.5	0.007493	0.035131	0.045571	0.023275	0.006238	0.001092	0.000145	0.000016	0.000002	0.000000	0.000000	0.118963
1.5	0.001862	0.037208	0.124421	0.134869	0.069947	0.022224	0.005085	0.000932	0.000147	0.000021	0.000003	0.396719
2.5	0.000243	0.009925	0.058954	0.104139	0.082259	0.037695	0.011892	0.002900	0.000591	0.000106	0.000018	0.308722
3.5	0.000025	0.001641	0.014342	0.035414	0.037573	0.022370	0.008912	0.002679	0.000660	0.000141	0.000027	0.123784
4.5	0.000003	0.000234	0.002734	0.008685	0.011517	0.008369	0.003989	0.001409	0.000402	0.000098	0.000022	0.037462
5.5	0.000000	0.000034	0.000502	0.001948	0.003088	0.002633	0.001449	0.000583	0.000187	0.000051	0.000012	0.010487
6.5	0.000000	0.000005	0.000098	0.000448	0.000824	0.000802	0.000498	0.000224	0.000079	0.000024	0.000006	0.003008
7.5	0.000000	0.000001	0.000021	0.000111	0.000232	0.000253	0.000174	0.000086	0.000033	0.000011	0.000003	0.000925
8.5	0.000000	0.000000	0.000005	0.000030	0.000071	0.000085	0.000064	0.000034	0.000014	0.000005	0.000001	0.000309
9.5	0.000000	0.000000	0.000001	0.000009	0.000023	0.000031	0.000025	0.000014	0.000006	0.000002	0.000001	0.000112
10.5	0.000000	0.000000	0.000000	0.000003	0.000009	0.000012	0.000011	0.000006	0.000003	0.000001	0.000000	0.000045
11.5	0.000000	0.000000	0.000000	0.000001	0.000003	0.000005	0.000005	0.000003	0.000002	0.000001	0.000000	0.000020
12.5	0.000000	0.000000	0.000000	0.000000	0.000002	0.000002	0.000002	0.000002	0.000001	0.000000	0.000000	0.000009
13.5	0.000000	0.000000	0.000000	0.000000	0.000001	0.000001	0.000001	0.000001	0.000001	0.000000	0.000000	0.000005
14.5	0.000000	0.000000	0.000000	0.000000	0.000001	0.000002	0.000002	0.000002	0.000001	0.000001	0.000000	0.000009
Col. sum	0.009626	0.084179	0.246649	0.308932	0.211788	0.095576	0.032254	0.008891	0.002129	0.000462	0.000093	100.06%

95%	Area below 95% curve
5%	Area above 95% curve

Table 2 Caribbean Sea wave scatter areas with 88% confidence for added resistance calculations

$H_s \backslash T_z$	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	Row sum
0.5	0.007493	0.035131	0.045571	0.023275	0.006238	0.001092	0.000145	0.000016	0.000002	0.000000	0.000000	0.118963
1.5	0.001862	0.037208	0.124421	0.134869	0.069947	0.022224	0.005085	0.000932	0.000147	0.000021	0.000003	0.396719
2.5	0.000243	0.009925	0.058954	0.104139	0.082259	0.037695	0.011892	0.002900	0.000591	0.000106	0.000018	0.308722
3.5	0.000025	0.001641	0.014342	0.035414	0.037573	0.022370	0.008912	0.002679	0.000660	0.000141	0.000027	0.123784
4.5	0.000003	0.000234	0.002734	0.008685	0.011517	0.008369	0.003989	0.001409	0.000402	0.000098	0.000022	0.037462
5.5	0.000000	0.000034	0.000502	0.001948	0.003088	0.002633	0.001449	0.000583	0.000187	0.000051	0.000012	0.010487
6.5	0.000000	0.000005	0.000098	0.000448	0.000824	0.000802	0.000498	0.000224	0.000079	0.000024	0.000006	0.003008
7.5	0.000000	0.000001	0.000021	0.000111	0.000232	0.000253	0.000174	0.000086	0.000033	0.000011	0.000003	0.000925
8.5	0.000000	0.000000	0.000005	0.000030	0.000071	0.000085	0.000064	0.000034	0.000014	0.000005	0.000001	0.000309
9.5	0.000000	0.000000	0.000001	0.000009	0.000023	0.000031	0.000025	0.000014	0.000006	0.000002	0.000001	0.000112
10.5	0.000000	0.000000	0.000000	0.000003	0.000009	0.000012	0.000011	0.000006	0.000003	0.000001	0.000000	0.000045
11.5	0.000000	0.000000	0.000000	0.000001	0.000003	0.000005	0.000005	0.000003	0.000002	0.000001	0.000000	0.000020
12.5	0.000000	0.000000	0.000000	0.000000	0.000002	0.000002	0.000002	0.000002	0.000001	0.000000	0.000000	0.000009
13.5	0.000000	0.000000	0.000000	0.000000	0.000001	0.000001	0.000001	0.000001	0.000001	0.000000	0.000000	0.000005
14.5	0.000000	0.000000	0.000000	0.000000	0.000001	0.000002	0.000002	0.000002	0.000001	0.000001	0.000000	0.000009
Col. sum	0.009626	0.084179	0.246649	0.308932	0.211788	0.095576	0.032254	0.008891	0.002129	0.000462	0.000093	100.06%

88%	Area below 88% curve
12%	Area above 88% curve

Table 3 Caribbean Sea wave scatter areas with 84% confidence for added resistance calculations

$H_s \backslash T_z$	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	Row sum
0.5	0.007493	0.035131	0.045571	0.023275	0.006238	0.001092	0.000145	0.000016	0.000002	0.000000	0.000000	0.118963
1.5	0.001862	0.037208	0.124421	0.134869	0.069947	0.022224	0.005085	0.000932	0.000147	0.000021	0.000003	0.396719
2.5	0.000243	0.009925	0.058954	0.104139	0.082259	0.037695	0.011892	0.002900	0.000591	0.000106	0.000018	0.308722
3.5	0.000025	0.001641	0.014342	0.035414	0.037573	0.022370	0.008912	0.002679	0.000660	0.000141	0.000027	0.123784
4.5	0.000003	0.000234	0.002734	0.008685	0.011517	0.008369	0.003989	0.001409	0.000402	0.000098	0.000022	0.037462
5.5	0.000000	0.000034	0.000502	0.001948	0.003088	0.002633	0.001449	0.000583	0.000187	0.000051	0.000012	0.010487
6.5	0.000000	0.000005	0.000098	0.000448	0.000824	0.000802	0.000498	0.000224	0.000079	0.000024	0.000006	0.003008
7.5	0.000000	0.000001	0.000021	0.000111	0.000232	0.000253	0.000174	0.000086	0.000033	0.000011	0.000003	0.000925
8.5	0.000000	0.000000	0.000005	0.000030	0.000071	0.000085	0.000064	0.000034	0.000014	0.000005	0.000001	0.000309
9.5	0.000000	0.000000	0.000001	0.000009	0.000023	0.000031	0.000025	0.000014	0.000006	0.000002	0.000001	0.000112
10.5	0.000000	0.000000	0.000000	0.000003	0.000009	0.000012	0.000011	0.000006	0.000003	0.000001	0.000000	0.000045
11.5	0.000000	0.000000	0.000000	0.000001	0.000003	0.000005	0.000005	0.000003	0.000002	0.000001	0.000000	0.000020
12.5	0.000000	0.000000	0.000000	0.000000	0.000002	0.000002	0.000002	0.000002	0.000001	0.000000	0.000000	0.000009
13.5	0.000000	0.000000	0.000000	0.000000	0.000001	0.000001	0.000001	0.000001	0.000001	0.000000	0.000000	0.000005
14.5	0.000000	0.000000	0.000000	0.000000	0.000001	0.000002	0.000002	0.000002	0.000001	0.000001	0.000000	0.000009
Col. sum	0.009626	0.084179	0.246649	0.308932	0.211788	0.095576	0.032254	0.008891	0.002129	0.000462	0.000093	100.06%

84%	Area below 84% curve
16%	Area above 84% curve

4 Seakeeping assessment

The seakeeping module of the route optimization method was implemented by NTUA-SDL within the EU funded ADOPT project by interfacing the seakeeping code NEWDRIFT and the probabilistic tool PROBAN (Spanos *et al*., 2008).

Seakeeping hazards can be formulated with a limit state function $g(X)$, where $X=(X_1, X_2, \cdots ,X_N)$ is a vector of random variables and takes negative values when a hazard occurs. Therefore the probability is calculated for the cases where:

$$g(X_1,\ X_2,\cdots,X_N)\ <\ 0 \qquad (3)$$

The presented limit state g-functions are mainly functions of ship responses in waves. By having the function S of the employed ship motion model, the ship responses Y, the wave and loading parameters X and some given response control parameters C, the g-function can be defined.

$$Y=S(X|C) \qquad (4)$$

$$g=g(X,Y|C) \qquad (5)$$

In realistic conditions each parameter of the sea-keeping problem, even sensitive to seakeeping ship inherent data such as the GM and radius of gyration, is related to a degree of uncertainty, whereas other parameters, such as the environmental data, are inherently random. Their uncertainty is not of the same importance for the calculations of the ship's responses.

The seakeeping module can be applied to both the ship's operational assessment and design procedure.

The operational mode parameters relevant to the ship's loading condition can be determined at the beginning of the voyage. In this mode the random variables are the environmental parameters. The speed and the heading to the wave constitute the control parameters. The short time of the calculations enables this mode for onboard probabilistic evaluation.

In the design mode, all of the variables are considered uncertain. This mode can be useful at the design stage for the risk assessment during the ship's life. The requested time for the probabilistic calculation does not allow this mode to be used on an onboard route optimization system.

4.1 Seakeeping hazards

In the development of the seakeeping module, five limit states (hazards) have been implemented, namely the vertical acceleration at the bow, the total acceleration at the bridge, the bow slamming, the propeller racing, and the deck immersion (green water). Hazards are defined either as excessive acceleration (exceeding threshold values) or high number of occurrences of seakeeping events. They are defined for several locations along the ship, which may be readily modified in a straight-forward method. Other hazards (e.g. bending moment) may be also added in the presently implemented system.

Formulation of limit states was used for the evaluation of the mean up-crossing rate of some variables. For the Gaussian, zero-mean, and narrow-band processes, the mean up-crossing rate v^+ of a level α can be approached by

$$v^+=\frac{1}{2\pi}\sqrt{\frac{m_2}{m_0}}\exp\left(-\frac{\alpha^2}{2m_0}\right) \qquad (6)$$

where m_0 and m_2 are the zero and second order moment of the variable's spectrum S_R in consideration. For linear ship responses, the S_R is calculated from the transformation of the wave spectrum by means of the response operator H, both functions of frequency ω.

$$S_R(\omega)=\left|H(\omega)\right|^2 S(\omega) \qquad (7)$$

4.2 Threshold values

The hazards are defined through a set of characteristic threshold values for the involved variables. Suppose the hazard of the frequent propeller racing that occurs during severe pitching and subsequent propeller emergences. Such an event is undesirable for the propulsion system. So, the capacity of the propulsion system and its tolerance of the racings is analyzed independently of the ship motions, and then the threshold value for the racing rate is determined and correlated consequences are attributed. If the frequency of propeller racing is higher than the determined threshold value, then the ship will encounter the related consequences. Apparently, for a hazard on a top level description several threshold values may be derived with each one correlated to a different level of consequences.

4.3 Probabilistic methods

For the evaluation of the probabilities of the seakeeping hazards, the first order reliability method (FORM), second order reliability method (SORM), and Monte Carlo method have been employed and investigated.

The FORM method initially transforms the basic X-variable space of a formulated limit state function $g(X)$ into a u-space, where variables U_i are independent and standard normal variables. The mapping does not change the distribution of the g-variable and preserves all relevant probability information. In this way, the transformed g-function divides the u-space into safe and failure domains, Fig.5, where g>0 and g<0 correspondingly. Then, if the g-function is substituted by a linear function which passes through a point u^*, the so-called design point, which is the point of the g-function closest to the space origin, a first order approximation is defined, namely the FORM method. Thus, the failure probability corresponds to the sub-domain defined by the linear approximation instead of the actual g-function (the shaded set in Fig.5). Applying the same concept, but implementing a second order approximation, the SORM (Second Order Reliability) method is defined.

Obviously if the limit surface g of a hazard is not strongly non-linear, then the approximation defined by FORM and corresponding probabilities could be satisfactory in view of the accuracy for the set problem.

The Monte Carlo method that is based on sampling of the evaluated function can be proved efficiently for the calculation of the central part of the distribution. Nevertheless, for low probability events it suffers from the large number of simulations required to achieve a level of accuracy.

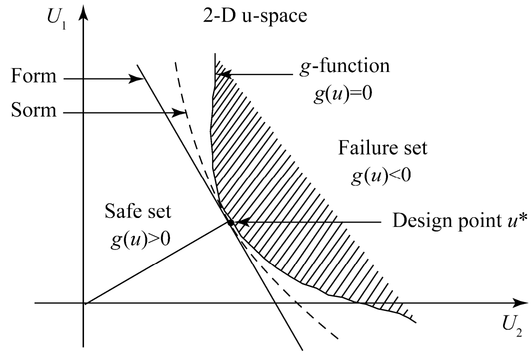

Fig.5 Two dimension *g*-function approach with FORM

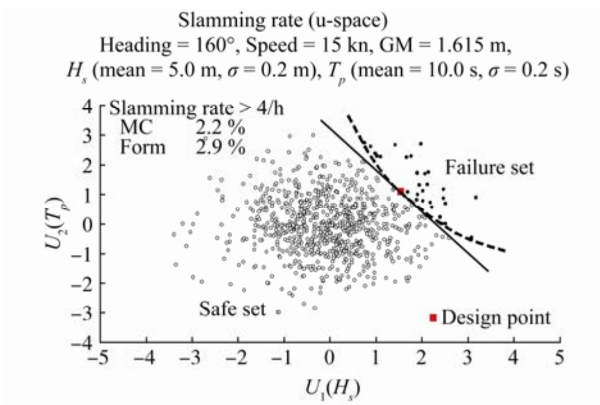

Fig.6 U-space for H_s and T_p

In Fig.6, the u-space mapping for the significant wave height H_s and the peak period T_p is shown for a slamming rate>4 per hour. The straight line is the linear approximation of the *g*-function according to FORM.

4.3 Computation time

A fast computational performance in order to achieve practical application times onboard is a basic requirement for the developed computer-based probabilistic approach. Although the computational time to complete a full set of calculations and evaluations strongly depends on the employed computer machine, the time recorded and provided herein enables a representative view of the current performance achieved in a laboratory environment.

With reference to a single PC, Intel Core2 CPU 6600 @ 2.40 GHz, 2 GB Ram, and for a dense hull representation (2×500 panels), the computational times are:

- 35 sec per limit state evaluation, when using Monte Carlo
- 5 sec per limit state evaluation, when using FORM.

An evaluation of 5 limit states takes about 12.5 min for the calculations of the probabilities for 30 alternative sailing conditions within a range of speed-heading combinations, as shown in Fig.7. For this assessment the wave spectrum parameters have been assumed to be uncertain parameters. The required time for the evaluation of five limit states can be considered short enough for the use of this module in an onboard Route optimization system.

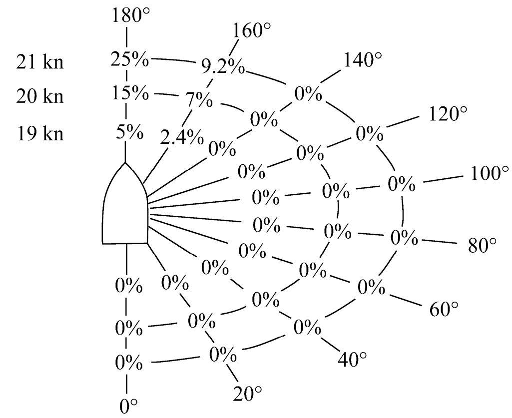

Fig.7 Probabilities for propeller emergence rate > (1/min)

5 Conclusions

A route optimization methodology aiming to improve the safety of the ship, the crew, and the cargo and also for the reduction of the total cost of the voyage has been briefly presented. Two of the main modules for the calculation of added resistance and the probabilistic assessment for the considered seakeeping hazards have been developed and validation studies proved their efficiency in view of their implementation into an on-board optimization system.

More seakeeping hazard limit states focusing on the structural integrity of the ship and the safety of the crew can be added and will be presented in planned future publications.

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