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MODERN NUMERICAL TECHNIQUES FOR THE SHIPS SAFETY ESTIMATION IN CRITICAL CONDITIONS

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Abstract: In this paper a method for a ship safety estimation at the preliminary stage of design is briefly presented. Solving a few hydrostatic and dynamical problems may be taken into account using the method with special regards to the ships safety estimation in critical conditions. The critical conditions may concern the problems of survivability caused due to the cargo and/or ballast shift, waves and wind impact including the ingress of external water into the watertight compartments of a ship.

The theoretical and computational models are briefly described. Using the computational model the safety assessment may be done for the initial event and scenario development assumed. Then, either some seakeeping, stability, damage stability or survivability related characteristics should be evaluated for the risk assessment. Both the seakeeping and stability characteristics are treated as the initial conditions for the risk assessment regarding the damage stability and survivability, and it usually follows from the hazard scenario development. The risk assessment is the base for the safety estimation. This is done according to the IMO regulations.

The computational model incorporates the modern numerical techniques and is briefly described by introducing the logical structure of design system, logical structure of computational model and a few application methods used.

The model enables to estimate the safety combining the influence of the hull form parameters, arrangement of internal spaces, loading condition including both the cargo distribution and permeability and impact of exciting forces. The exciting forces may follow from both the external and internal sources. And they are as follows: waves, wind and cargo and ballast shift.

Keywords: design of ships, ships hydromechanics, safety of ships, design for safety

1. Introduction

Today we have a competitive shipbuilding market where design enquires require rapid response. It may be observed that many new ship designs concern modern one–off vessels and a particular design office may not have had any previous experience. And this can generate the potential risk concerning the design process. A ship design is usually connected with satisfying a set of often conflicting requirements. This is why most design proposals are a compromise to some extent. And the best compromise may be achieved using some kind of multiobjective optimization approach or by carrying out a lot of parametric–variation type investigations. To do that a suitable computer software should be used, particularly when there is a short time scale associated with preparation of design proposals. It occurs that the amount of suitable software for use at either the concept or preliminary design stage is small indeed.

The preliminary stage of a ship design process is an area where there are very few useful software tools which respect the demands of later design stages and most of the software tools available are mainly intended for use at the later stages of design development. The quantity and quality of data demanded by such systems make them very little useful at the ealier design stages (conceptual or preliminary) when the information available my be incomplete and often of poor standard. Some software tools have recently been developed which attempt to bridge this substantial gap in the range of computer–based tools available to the designers.

The current challenges in ships design require further development of design systems to meet new requirements. Big advances in hydro–numeric techniques, computer hardware, tool software, computer graphics, networking and databases show the wealth of new technology which is being incorporated into design practice. The current application design codes are often equipped with new theoretical approximations and unfamiliar numerical techniques. Run on supercomputer architectures they give a great amount of textural, numerical and graphical details. Today, we may observe a growing interest in acquiring, transitioning and managing new technology in ship design. The newest technologies coming into design practice are as follows: expert systems, neural networks and parallel computing.

From the information mentioned above it follows that there is a need to build modern design tools which could enable to satisfy the modern design challenges in the form of new design requirements. Building the novel computer–based design codes we find ourselves in front of using modern numerical techniques associated with both modern tools and application software.

All the problems regarding using the modern design codes are even more complicated when they should deal with the design options for both efficiency and safety. Then, despite of the ordinary design requirements associated mainly with the efficiency and economical aspects, there is a set of the so–called safety related requirements.

In this paper a method and computational model for ships design for safety are briefly introduced with special attention towards the application of modern numerical techniques. But before that some information on computer applications regarding safety is given.

2. Current computer applications regarding safety

Following the "Estonia" passenger ferry disaster the project entitled "Safety of Passenger/RoRo Vessels" was established by the Nordic countries. It concerned the stability and safety requirements for new passenger/RoRo vessels with special regards to the damaged and flooded conditions. The work was aimed at establishing an entirely new risk based stability standard including developing the survivability criteria.

The following problems have been studied [1]:

1. damage stability modelling methods;
2. watertight integrity;
3. collision damage extent and
4. dynamic effects in waves.

The main tasks of the project were as follows [1]:

Task 1: Damage stability modelling methods;
Task 2.1: Damage Extent
Task 2.2: Large Scale Flooding
Task 3: Dynamic Effects in Waves
Task 4: Cargo Securing and Cargo Shift
Task 5: Development of Survival Criteria for RoRo Vessels in Damaged Condition
Task 6: Framework for New Damage Stability Standard
Task 7: Example Design
Task 8–10: Safety Assessment

The results of the project contained three important new elements [1]:

1. minor damage concept;
2. probability of survival;
3. major damages.

There is the SAFER–EURORO programme directed by the Ship Stability Research Centre at the Strathclyde University in the United Kingdom. This is a multi–disciplinary research programme for developing an integrated approach to designing safe passenger/RoRo ferries and to implement this approach to actual design examples. The programme is structured as a cluster of individual projects, each addressing a special area in ship design and operation.

According to this, four projects are considered [2]:

Project 1 — *Structural Damage Risk (DAMRISK) consisting of five tasks*;
Project 2 — *Design for Survivability (DESURV) consisting of seven tasks*;
Project 3 — *Successful Mustering and Evacuation (SMUExit) consisting of five tasks;*
Project 4 — *Seaworth including six tasks.*

The first three projects comprise the original SAFER–EURORO programme and they concern the following problems [2]:

Project 1: — *Collision and Grounding Damage*

- Wave — Induced Slamming Damage;
- Structural Integrity;
- Risk Assessment of Collision and Grounding Damage;
- Structural Design for Safety;

Project 2: — *Damage Survivability*

- Hydrodynamics of Flood Water;
- Water Ingress by Model Tests;
- Progressive and Transient Flooding;
- Sloshing and Dynamic Stability;
- Risk Assessment of Large—scale Flooding;
- Design for Ship and Cargo Survival;

Project 3: — *Mustering Model*

- Evacuation Model;
- Decision Support Model;
- Risk Assessment and Management of Passenger Evacuation;
- Design for Passenger Survival.

During the above mentioned projects the following problems have been solved [3, 4]:

1. mathematical/numerical modelling:
   - generalised mathematical model;
   - modelling the water ingress;
   - validation/calibration of the mathematical model;
2. comparative study:
   - wave environment;
   - comparison between numerical tests and physical model tests;
   - comparison between SOLAS 90, SOLAS 90+50 and numerical simulations.

According to the above published information there has been a big progress in ships survivability investigations. But it certainly will take many more years to put the new regulations regarding the safety of ships in damaged and flooded condition into power. There is a necessity to develop the international collaboration links regarding all the described problems, too.

In Poland there has been a set of reserch projects concerning the ships safety problems. Among them there is a research project No. 9 T12C 026 16 founded by the Scientific Research Council KBN which concerns a new method for the ships safety estimation in critical conditions and it will terminate by the end of 2000. The following paper presents a few aspects connected with the project, too.

3. Modern approach to ships safety

The safety of ships still lies among the most important aspects of modern Marine Technology. To confirm this we may find a lot of tragic examples regarding the safety of navigation at sea [5–10]. The best known disasters which happened during the past few years are as follows:

1. Loss of the ro–ro passenger and vehicle ferry “Herald of Free Enterprise” on 6th March 1987;
2. Loss of the ro–ro passenger and vehicle ferry “Jan Heweliusz” on 14th January 1993;

3. loss of the ro–ro passenger ferry "Estonia" on 27th September 1994.

The accident of the Polish ferry "Jan Heweliusz" which sank on the Baltic Sea, very close to the Arcona Peninsula on 14th January 1993, was very tragic. And it had brought a lot of scientific and practical investigations. Twenty two Polish seagoing ships were lost between 1946 and 1993. And about one hundred twenty eight people died during those tragedies. The most dramatic among them were the accidents of the following ships [11]:

1. m/s "Mazurek" — a bulk cargo ship, lost in abnormal conditions on the Baltic Sea in 1963, six mariners died;
2. m/s "Nysa" — a general cargo ship, lost in abnormal conditions on the North Sea in 1965, all eighteen mariners died;
3. m/s "Kudowa Zdrój" — a general cargo ship, lost in abnoramal conditions on the Mediterranean Sea in 1983, twenty mariners died;
4. m/s "Busko Zdrój" — a general cargo ship, lost in abnoramal conditions on the North Sea in 1985, twenty four mariners died;
5. m/f "Jan Heweliusz" — a cargo–passenger ferry, lost in abnormal conditions on the Baltic Sea in 1993, fifty four men died including twenty mariners.

The majority of these ships met abnormal conditions during the accident. But the reasons of accidents at sea have always been both very complex and difficult to explain, particularly when all the mariners and passengers lost their lives. There are complex reasons for most accidents and they depend on many factors. Despite of all the efforts undertaken to explain each accident separately there is a growing interest to possess an International Safety Code for the ships. This task is difficult and requires a lot of work.

From the general point of view the following factors may secure a ship at sea [12–14]:

1. human factor;
2. control systems / technical means
3. legislative actions.

And these are the factors of first level . There are existing interrelations between them and they play the major role for the ship safety. Then, there is another group of factors which have an immediate influence on each ship safety at sea and the most important among them are as follows [14, 15]:

1. ship parameters/characteristics including hull, propeller and rudder particulars;
2. cargo parameters/characteristics including arrangement of internal spaces, cargo and ballast distribution and loading condition;
3. environment parameters/characteristics including wind, waves and current;
4. operational parameters/characteristics connected mainly with the integrated ship management system if available; if not, then both the navigational aids and information available on board are very important (ship speed and course angle);
5. human factor including both the psychological and physical predispositions, character, morale, integrity, knowledge, experience and training degree.

And these are the factors of second level.

The ship safety domains such as stability, survivability or manoeuvrability depend on a complex set of parametrs which belong to the different factors from either the first or second levels. For example, the stability safety depends on the following factors: hull form particulars, hull form coefficients, hull form itself, hydrostatics, cargo and ballast distribution and their permeabilities, loading condition including the ship centre of gravity, etc... . After we know all the above mentioned it can be possible to calculate the intact stability characteristics. Then we can estimate stability according to the IMO standards, for example. But, stability also depends on the environment characteristics such as the wind, waves and current parameters. Moreover, it depends on the human factor and all the control systems, technical means and legislative actions including the existing design and operational regulations (Question: Should they be the same?).

Next there are interrelations between the safety domains, such as between both the stability and manoeuvrability, stability and survivability, stability and seakeeping or stability, manoeuvrability and seakeeping. All of them often depend on the same factors of the second level for example. The interrelations between the safety domains and the interrelations between certain hydromechanic characteristics/parameters are the reason why a common complex set of such parameters they depend on is necessary to create. These parameters should be the factors of third level.

Taking into account the interrelations among the factors at different levels and the interrelations among the factors at the same level we may come to the conclusion that applying the system approach for the ship safety estimation is both very complicated and difficult tool to use. But the first step is done and a structure of the levels of factors affecting a ship safety may be presented as in Figure 1 [14].

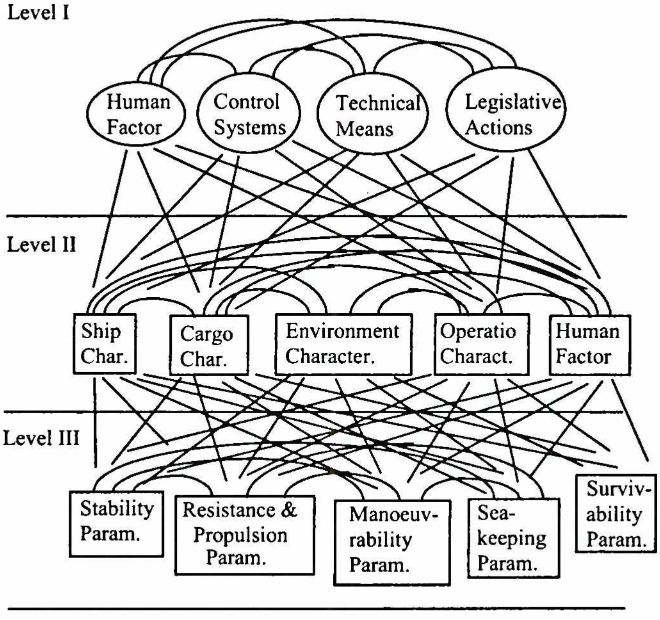


Figure 1. Levels of factors affecting a ship's safety.

When a ship meets abnormal conditions all the factors discussed are very important from the safety point of view but the key role between them play these which are the most important from the ship's dynamics point of view. They can easily be found within the seakeeping model structure.

The major source of information on hazards and risks involved in shipping are both the statistics and investigations into serious casualties [11][16-18]. Studing these data it becomes clear that the safety of life at sea and the pollution of the environment are a function of the actual ship's design, operation and maintenance conditions. Therefore an integrated rational framework is necessary to be worked out. Such a framework should apply the approach based on risk acceptance criteria (if available) combining both the design and operational features, ageing, safety and pollution prevention aspects.

Taking all the above into account a method for safety estimation has been suggested. The method is associated with a few ship's safety problems reagarding both the naval architecture and ship hydromechanics and it is novel to some extent.

4. A method for ships safety estimation in critical conditions

A proposal of Intregrated Ship Safety Estimation Method (ISSEM) has been prepared towards solving the safety problems in critical conditions and it includes the theoretical and computational models. The theoretical model describes both the global and technical approaches used by the method. The computational model uses these approaches in the form of a dynamic data base.

The global approach adopts some knowledge from the Formal Safety Assessment method which is combined with the integrated system approach described in Chapter 3 [19–22]. The basic assumptions when applying the global approach were as follows [14]:

1. ship operation is associated with risk from the safety point of view;
2. safety measures should be quantified, as without these you can not manage the safety;
3. ISSEM method should be applicable.

The global approach has enabled to prepare the ISSEM method framework as follows [14, 23, 24]:

1. method philosophy development including reviewing literature, estimating safety of existing vessels, reviewing regulations, etc.;
2. ship and environment definition;
3. hazard and scenario identification;
4. hazard and risk assessment;
5. hazard resolving and risk reduction;
6. cost/benefit analysis;
7. decisions made on ship safety (selection of optimal design, operational and mitigation measures).

Finally the ISSEM method should enable to prepare a Safety Code proposal.

The technical approach is connected with developing the following [14, 23, 24]:

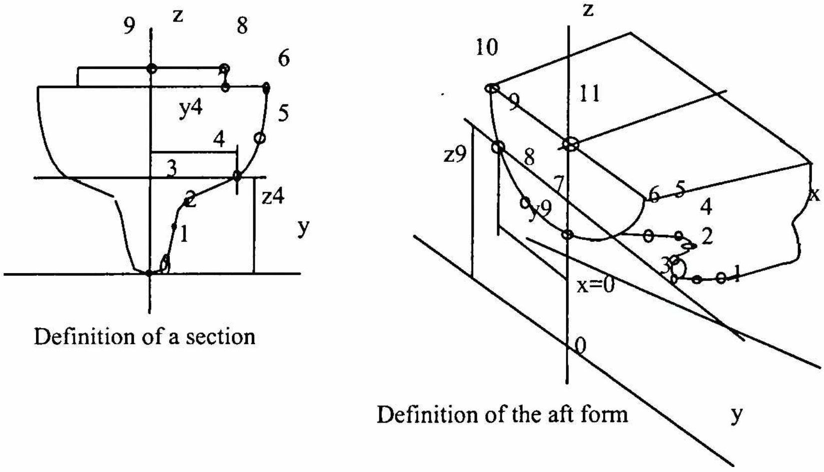
1. logical structure of ISSEM design system;
2. logical structure of ISSEM computational model;
3. both analytical and numerical methods for ISSEM;
4. application methods for ISSEM.

4.1. Ship and environment definition

Among the most important elements of the ship (hull form) definition are as follows [14]:

1. hull form representation:
    - generally it consists of main parameters and hull form coefficients;
    - it is presented by the cross sections with changeable number of waterlines at each section;
    - dynamically interpolated sections have been introduced to increase the accuracy of numerical calculations;
    - singularities of the hull form are taken into account, too;
    - during the calculations the hull form is mainly represented by the network of both the linear and parabolic functions and cubic or b– splines;
2. arrangement of internal spaces:
    - it is generated according to both the existing classification and operational rules;
    - it can be evaluated by the survivability analysis, too;
3. watertight compartments form representation:
    - it is interpolated according to the hull form representation and arrangement of internal spaces data.

Examples of null form representation



Definition of a section

Definition of the aft form

Figure 2. Examples of a ship's definition.

The above mentioned elements enable to obtain the characteristics which are fully specified in Chapter 4.3.

The propeller and rudder are separately defined by their hydrodynamic coefficients. But the direct methods to calculate their hydrodynamic characteristics may be applied as well. Some examples concerning a ship (hull form) definition are presented in Figure 2.

The environment description consists of the wave and wind definitions. Despite of different application methods used by the ISSEM method, the regular wave theory and pseudo spectrum approach (similar to the St.Denis & Pierson method) are used for the wave definition [14, 25]. The main idea of this approach is to substitute the real frequency by the encounter one:

$$\omega_E = \omega - (\omega^2/g)\, v_S \cos\gamma, \tag{1}$$

where: ω_E — encounter frequency;
ω — real frequency;
v_S — heading speed;
γ — ship course angle according to the wave propagation direction.

Using the pseudo spectrum approach the irregular waves are presented as a Fourier series expansion by the encounter frequencies:

$$\zeta_W(t) = \zeta_{Wi} \sin(\omega_{Ei}\, t + \varepsilon_i), \tag{2}$$

where: ε — random number with constant distribution in range [0, 2Π];
ζ_{Wi} — amplitudes of harmonics calculated using the JONSWAP spectrum or another [25][27];
$\zeta_W(t)$ — wave amplitude.

The wind is defined by the apparent wind speed v_A used for the wind resistance calculation [26]. And it depends on the ship's speed v_S, real wind speed v_W and ship's course angle according to wind β_W as follows:

$$v_A = v_S^2 + v_W^2 - 2v_S + v_W \cos\beta_W. \tag{3}$$

4.2. Hazard and scenario identification

The major hazards on board ship include [16]: ship casualties, human casualties, failures, pollution and lawful acts. In this work we have mainly been interested in the ship casualties from the hydromechanic point of view and the hazard identification is closely connected with the system approach applied by the ISSEM method. The following methods can be used to identify the hazards [14, 16]: casualty statistics, failure rates, failure mode and effect analysis, hazard and operability studies (HAZOP). Up to now the casualty statistics have been applied by the ISSEM method. The statistics were taken from the publications: [11, 16–18]. All the statistics have been put into the DHDB Dynamical Hydromechanic Data Base shortly described in Chapter 5. Considering the potential hazards and initiating events it is possible to identify the significant accidental scenarios. Such an analysis needs a lot of both the model tests and full scale trials

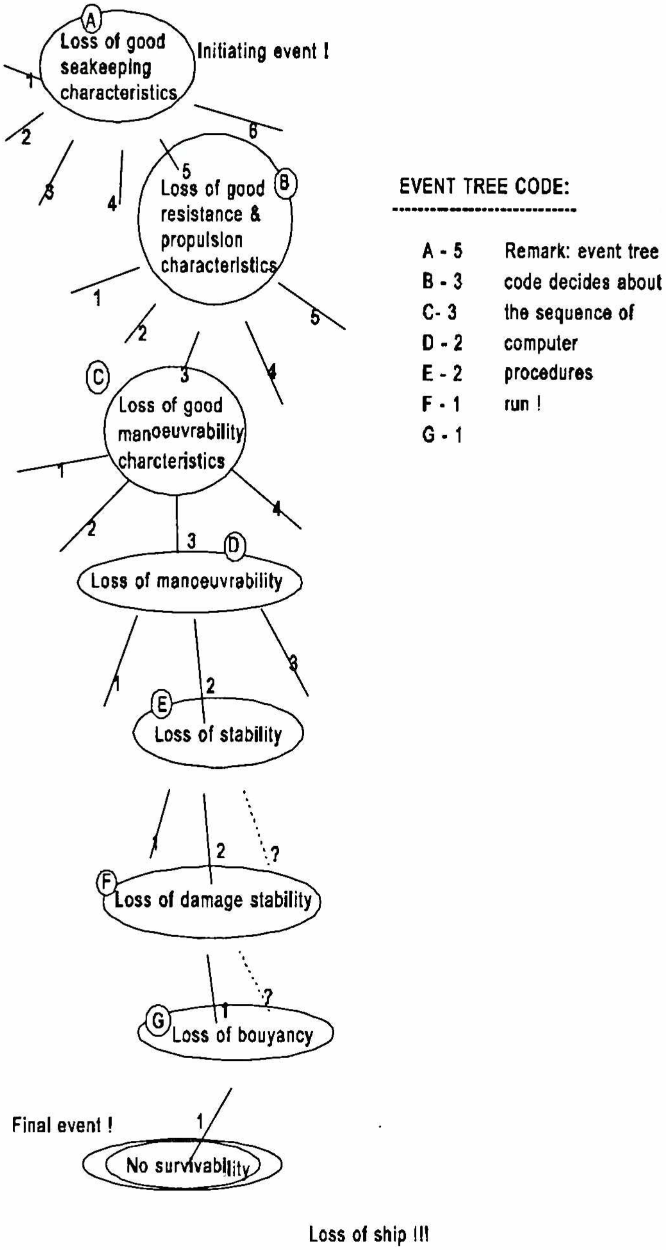


Figure 3. A simple ISSEM event tree.

data, as well as numerical simulations. This is in order to identify the consequences of initiating events. The event tree analysis, fault tree analysis, cause consequence analysis and escape, evacuation and rescue analysis may enable to assess how the initiating event arises and how the consequences look like.

A simple ISSEM event tree analysis for a cargo–passenger ferry accident is presented in Figure 3 [14].

Analysing the factors of the first, second and third levels it has been decided that the exciting forces may follow from:

- external sources: wind, wave and current defined as the environment;
- internal sources: cargo and ballast shift.

Other exciting forces as the rudder hydrodynamic force were not taken into account at this moment.

4.3. Hazard and risk assessment

The hazard and risk assessment needs the hydromechanic design procedures to be combined with the risk assessment methods. According to the hazard and scenario identification the relevant hazard and risk assessment procedures should be applied for the safety estimation. As an example the risk assessment may concern the seakeeping, stability, damage stability and survivability domains for the ISSEM event tree presented in Chapter 4.2.

The logical structure of the computational model presented in Chapter 5.2 shows how the following assessment methods have been applied. It is clearly shown in Figure.7 that before both the seakeeping, stability, damage stability and survivability assessment is initiated, the following modules of the ISSEM Dynamical Hydromechanic Data Base for the given ship should be prepared:

1. hull form representation;
2. arrangement of internal spaces;
3. watertight compartments form representation;
4. estimation of hydrostatic characteristics for undamaged ship including:
   - Bonjean scale;
   - hydrostatics;
   - cross curves of stability;
5. estimation of hydrostatic characteristics of watertight compartments and tanks including volumes;
6. estimation of loading condition including:
   - light ship weight;
   - distribution of cargo, ballast and stores;
   - permeabilities;
   - centre of gravity;

Generally, the risk assessment can be done independently for the seakeeping, stability, damage stability and survivability for the given separate initial conditions from the design point of view. But the ISSEM computational model enables to follow the ISSEM event tree accepted and then the risk assessment can be done when the poor seakeeping characteristics may cause the problems with stability. And if the cargo and ballast shift can happen for the given wind and waves it may be followed by a hull skin damage for example. After that, both the damage stability and survivability assessment may show if the ship is able to survive in critical conditions.

It must be clearly indicated that the main objectives of the ISSEM method are both the risk assessment and safety estimation of a ship in critical conditions specified often as the damaged conditions. Taking into account that the above mentioned analysis should deliver the proper conclusions regarding safety it is necessary to use the seakeeping and stability modules within the ISSEM computational model.

Risk assessment for seakeeping

When the seakeeping is under consideration then the following degrees of freedom are taken into account [25]: rolling, pitching, heaving, surging and swaying. The system of differential equations describing a ship motion in waves is as follows:

$$\begin{aligned}
&(m + m_{11})\, \ddot{\xi}_G + \lambda_{11}\, \dot{\xi}_G = F_\lambda(t),\\
&(m + m_{22})\, \ddot{\eta}_G + \lambda_{22}\, \dot{\eta}_G = F_\eta(t),\\
&(m + m_{33})\, \ddot{\zeta}_G + \lambda_{33}\, \dot{\zeta}_G + \gamma S_{WL}\zeta_G + m_{33}\ddot{\psi} + (\lambda_{35} + vm_{33})\, \dot{\psi} +\\
&(\lambda_{33} - \gamma S_{WL}(x_f - x_g))\, \psi = F_\lambda(t),\\
&(I_X + m_{44})\, \ddot{\phi} + R(\dot{\phi}) + D\, GM\phi = M_\phi(t),\\
&(I_X + m_{55})\, \ddot{\psi} + (\lambda_{55} + (v^2/\omega_E)\lambda_{33})\dot{\psi} + (\gamma I_{WL} - vm_{33})\, \psi + m_{35}\ddot{\zeta}_G +\\
&\lambda_{35} - vm_{33})\, \dot{\zeta}_G + (-\gamma S_{WL}(x_f - x_g) - v\lambda_{33})\, \zeta_G = M_\psi(t),
\end{aligned} \tag{4}$$

where: m — ship mass;

$m_{11}, m_{22}, m_{33}, m_{44}, m_{55}$ — corresponding added masses;
$\lambda_{11}, \lambda_{22}, \lambda_{33}, \lambda_{44}, \lambda_{55}$ — corresponding wave damping coefficients;
$\xi_G, \eta_G, \zeta_G, \phi, \psi$ — surging, swaying, heaving, rolling and pitching motions;
$F_\lambda(t), F_\eta(t), F_\zeta(t)$ — corresponding exciting forces;
$M_\phi(t), M_\psi(t)$ — corresponding exciting moments;
x_f — abscissa of the centre of waterplane area;
x_g — abscissa of the centre of gravity;
I_{WL}, S_{WL} — inertia moment of the waterplane area and waterplane area.

The coupling between pitching and heaving is taken into account, too. The hydrodynamic components of the exciting forces are ignored in rolling and heaving where the restoring terms exist. The seakeeping computational model enables to obtain the significant values of roll, pitch, surge, sway and heave accelerations and comparing them with the officially adopted seakeeping standards. The yaw motion is fully undertaken by the manoeuvrability computational model. To get the full information for the safety decission process it is necessary to know the contribution of each motion to the full acceleration vector at a given ship point. The roll contribution should be considered as the most significant when ship at the beam position. In the ISSEM method the importance of each motion contribution can be taken into account according to both the hull form particulars, sea environment parameters, loading condition data, heading speed and course angle, human factor and technical devices used by the ship (conditionally). The risk assessment can be done when the changes of accelerations are traced according to the changes of the hull form and environment parameters.

The seakeeping assessment can be done according to the seakeeping performance criteria published by E. Lewis in [34].

When the seakeeping assessment is finished then the problem of risk assessment for seakeeping can be approached. According to the above mentioned the risk assessment is based on the standard deviation of all the components (sway, surge, pitch, roll and heave) of full acceleration vector in the given point of the hull form [14, 25]. The criteria is proposed to be as follows:

$$K1 = \sqrt{V_{ax} + V_{ay}}, \qquad (5)$$

$$K2 = \sqrt{V_{ax} + V_{ay} + V_{az}},$$

where: K1 — number giving the estimation of stability of both the human and equipment due to the lateral inertia action caused by the ship's motion;

K2 — number giving the estimation of stability of both the human and equipment due to the three–dimensional inertia action caused by the ship's motion;

V_{ax}, V_{ay}, V_{az} — variances of both the x, y and z components of the full acceleration vector calculated as it is published in [25].

There is an example of the risk assessment for seakeeping presented in Chapter 5.2.

Risk assessment for stability and damage stability

The stability assessment can be done using either the cross curves or constant displacement method. Of course, the stability is evaluated according to the current loading condition. The loading calculations are based on the arrangement of internal spaces and cargo, stores and ballast distribution, using the iterative approach. When the full information on the loading condition is achieved and the centre of gravity is known, the stability righting arms can be obtained.

The damage stability assessment concerns calculation of the residual stability characteristics for a ship in damaged condition. This is a typical naval architecture problem involving both the linear, two–dimensional and three–dimensional integration. The cross curves method for the damaged ship may be used to obtain the residual stability characteristics. But the more advanced method for the damage stability calculation seems to be the Krylov–Dargnies constant displacement method [35, 36]. It is based on the properties of equivolume waterplanes where two equivolume water lines inclined at $\Delta\phi$ angle to each other are tangential to a cylinder. Of course, the radius of cylinder varies with ϕ angle of heel but if $\Delta\phi$ angle is relatively small, less than 5 degrees for example, the r radius of the cylinder may be assumed to be constant. This method is fully presented in [13, 35, 36].

Finding the constant displacement waterlines inclined at different angles becomes a less time–consuming exercise than by the usual iterative method based on the longitudinal integrations of sectional areas (cross curves method). Both the stability and damage stability characteristics are checked against the IMO stability and damage stability criteria [28].

Having both the stability and damage stability assessed it is possible to start the risk assessment procedures.

The probabilities of capsizing for both the intact and damage stabilities have been defined as follows [37]:

$$P_{CI} = 1 - P_{SI}, \qquad (6)$$
$$P_{CD} = 1 - P_{SD},$$

where: P_{CI}, P_{SI} — probabilities of capsizing and stability for intact stability-conditions;

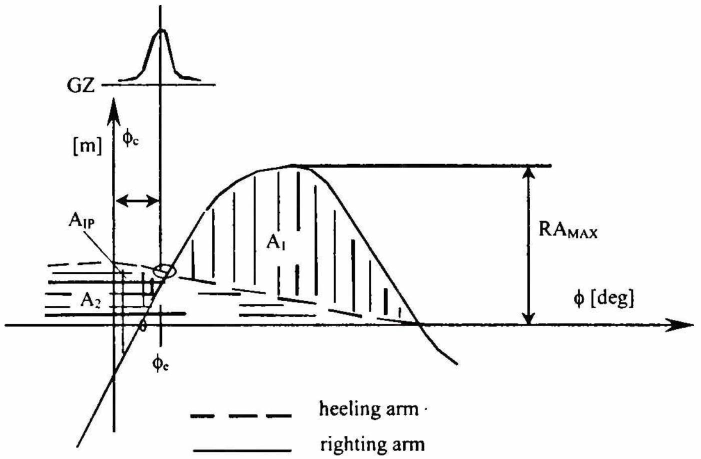
P_{CD}, P_{SD} — probabilities of capsizing and stability for damage stability conditions.

Then, the probability of stability for both the intact and damage stability conditions can be determined as follows:

$$P_{SI} = P\ (((HA_{IP} <= 0.7\ RA_{MAX}) \cup (A_I >= 1.3\ A_2))), \qquad (7)$$
$$P_{SD} = P\ (((\phi_c <= 20°) \cup (A_I >= 1.3\ A_2))).$$

All the variables used in equations (7) are presented in Figure 4.

TRANSVERSE STABILITY CRITERIA



Example: Ship in damaged condition

Figure 4. Definition of parameters and variables for the risk assessment for stability and damage stability.

It follows from (7) that the performance function is

$$A_I < 1.3\ A_2 \qquad (8)$$

for example, and the capsizing occurs when:

$$A_I - 1.3\ A_2 < 0. \qquad (9)$$

Then the P_C probability of capsizing can be given as the integration of the joint probability density function of $X_{RV} = (X_1, X_2, ..., X_n)$ random variables:

$$P_C = P(A_1 < 1.3A_2) = \int_{-\infty}^{+\infty} f_{A_1}(x) \cdot f_A(x)\, dx, \tag{10}$$

where: A_1 — $1.3A_2 < 0.1$;

$f_{A_1}(x)$ — cumulative distribution function of A_1;

$f_A(x)$ — probability density function of $1.3A_2$.

In Figure 4 the logical structure of model for the risk assessment for stability and damage stability is presented.

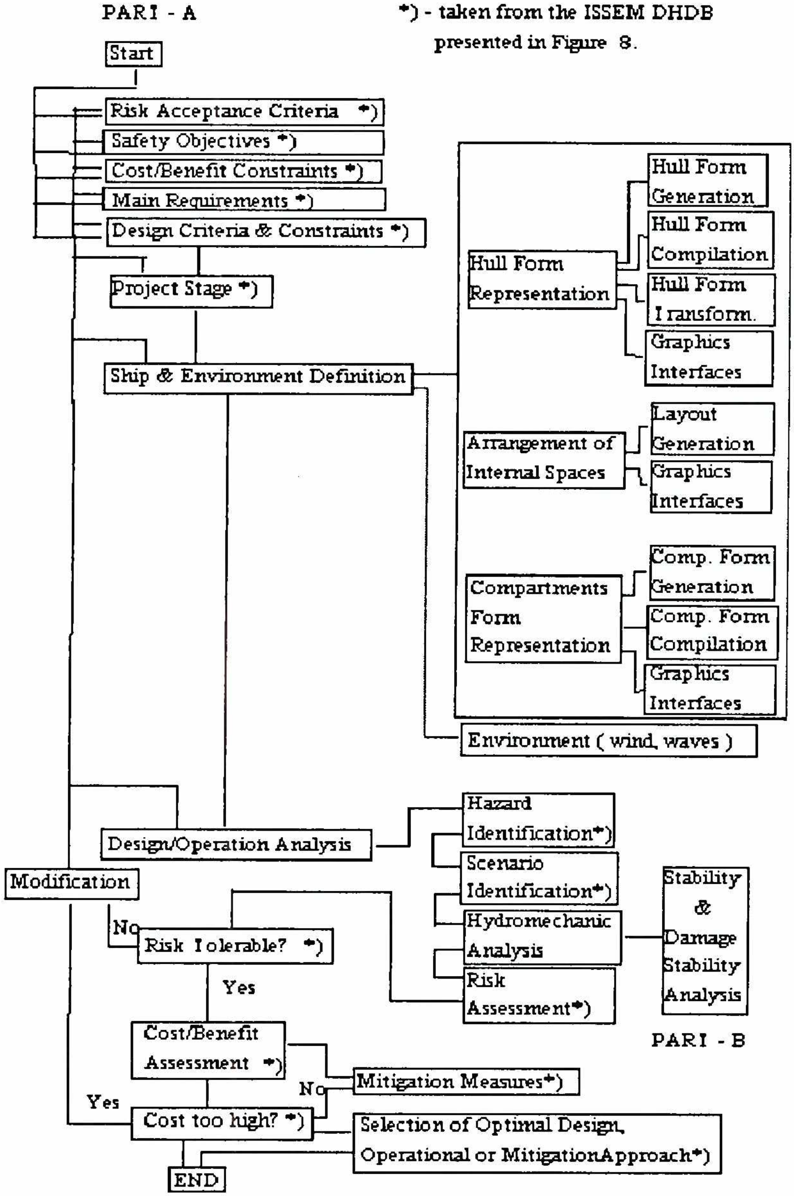


Figure 5. Logical structure of model for the risk assessment for stability and damage stability.

It is necessary to indicate that the current computational model does not take into account all the dynamical problems associated with both stability and damage stability. But these problems should be incorporated according to the schedule of KBN project mentioned before.

Risk assessment for survivability

The probabilistic concept has been adopted for the ISSEM survivability assessment and the algorithm was presented in the following papers [13, 29]. The risk assessment for survivability is connected with calculating the survivability index A as follows [35]:

$$A = \sum_{i} p_i s_i , \tag{11}$$

where: p_i — probability of flooding any group of compartments,
s_i — probability of surviving of flooding any group of compartments.

An example of the risk assessment for survivability is presented in Figure.9.(see the ISSEM Dynamical Hydromechanic Data Base introduced in Chapter 5.2).

Additional procedures regarding the resistance, propulsion and manoeuvrability assessment

It has been mentioned that the proposed method is directed towards the ships safety estimation in critical conditions. The critical conditions are closely related to the damage conditions of a ship when both the internal and external impacts have a big influence on the ship survivability. Sometimes there is a need to identify the initial events better, according to the fault tree. This is why the seakeeping assessment procedures are incorporated into the ISSEM method structure. For the same reason the resistance and propulsion modules may be provided. The manoeuvrability module could be useful as well. The manoeuvrability characteristics are very important from the safety point of view. For example, the exciting beam forces generated by both the rudder and propeller may be taken into account when the stability in critical conditions is evaluated [30]. Even, if their influence on stability may be small.

The resistance and propulsion algorithms are taken from [31]. The modular approach has been applied for the manoeuvrability calculation [32]:

$$\begin{aligned} m(\dot{u} - rv) &= X_H + X_P + X_R + X_E, \\ m(\dot{u} + rv) &= Y_H + Y_P + Y_R + Y_E, \\ I_Z \dot{r} &= M_H + M_P + M_R + M_E, \end{aligned} \tag{12}$$

where the H, P, R indices are describing the Hull, Propeller and Rudder generated exciting hydrodynamic forces. The E index is presenting the environment exciting forces from both the wind, waves and current.

The results of risk assessment (scientific calculations) should be compared with the assigned risk targets. There are a few methods to show the acceptable risks in comparison with the intolerable one and they are as follows [16]:

1. ALARP (As Low As Reasonably Possible) concept;
2. F–N curve;
3. Risk acceptance matrix.

The third one has been accepted for the ISSEM method. The following division of risk levels was introduced according to the frequency and consequence categories: broadly acceptable, acceptable with controls, undesirable and unacceptable.

4.4. Hazard resolving and risk reduction

The risk reduction decisions should be made by designers, operators and safety managers. They can be very different depending on the stage of the design process. Table 1 presents an example from the ISSEM model where the risk reduction decisions depend on the intolerable risk values.

Table 1.

Stage of the Project	Intolerable Risk Values concerning:	Risk Reduction Decisions
conceptual	poor intact stability and metacentric height to small	changing main particulars values and/or position of centre of gravity
preliminary	poor intact stability and metacentric height to small	changing hull form representation including body lines, changing arrangement of internal spaces and/or position of centre of gravity
detailed/operation	poor intact stability and metacentric height to smal	changing cargo and/or ballast distribution

The knowledge based on both the intolerable risk values and risk reduction decisions can be complicated mainly due to the number of project stages, loading conditions, environment loads, ship speed and course. Therefore, the decision making process should be controlled by both the designer, operator or safety manager and knowledge–based system.

4.5. Cost/benefit analysis

The problems regarding the cost/benefit analysis are not discussed in this paper and they are outside of the author's professional interests. They should be solved by the experts on economy, marketing, ships manufacturing and safety of navigation.

4.6. Decisions made on ship safety (selection of optimal design, operational and mitigation measures). Safety objectives

Having established the risk acceptance criteria we may identify the safety and environmental protection objectives which should be known for a given operation

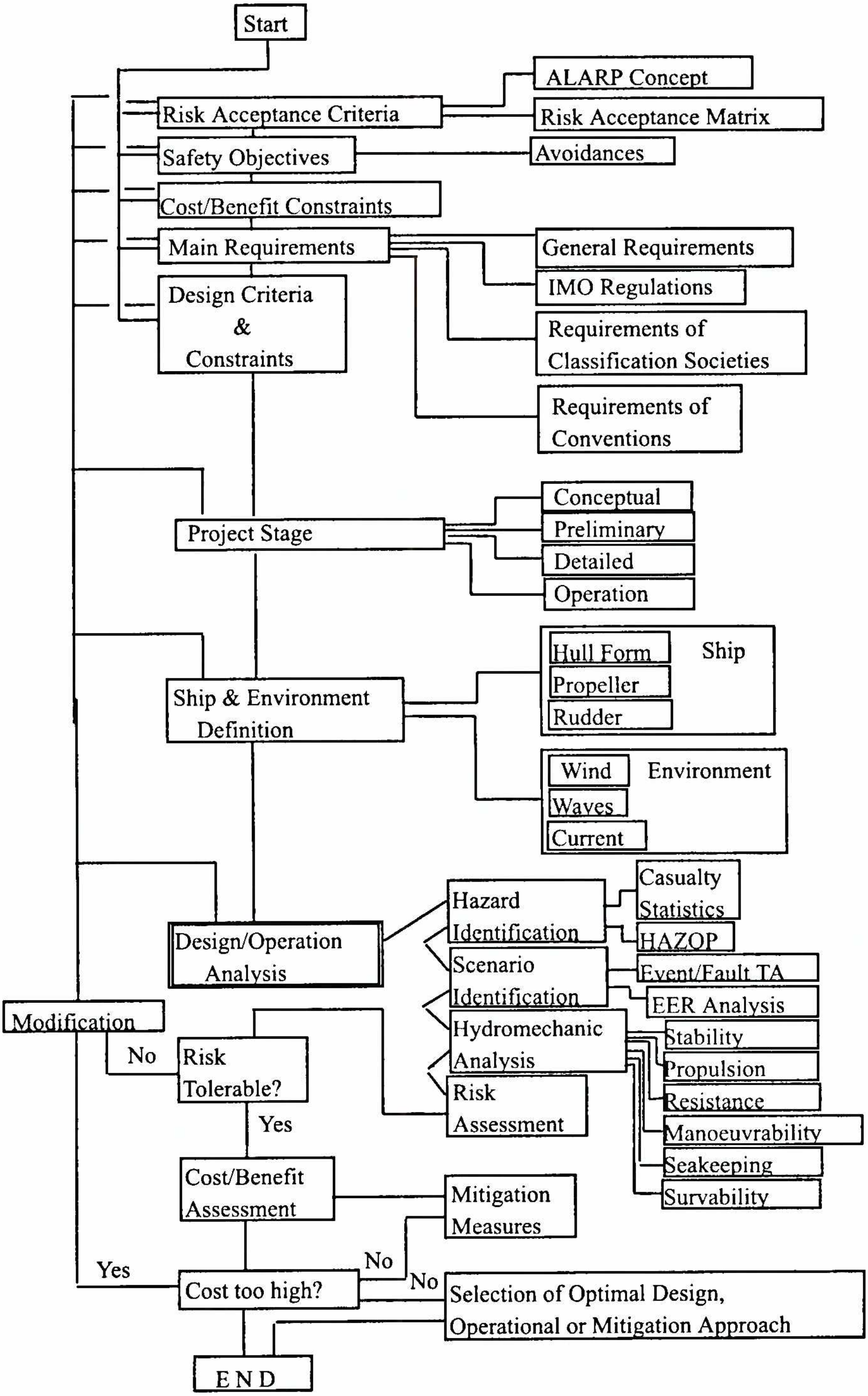


Figure 6. Logical structure of the ISSEM design system.

to avoid hazardous situations and accidents. The safety objectives could be as follows: avoidance of injuries, death, ship's loss or spillage of oil. They may be introduced in the form of a ISSEM safety code presented as an example in Table 2.

Table 2.

Safety level	1	2	3	4
Effect on crew, passengers, ship	normal, nuisance	operating limitations	significant reduction in safety margins, injuries	very serious injuries, deaths, loss of ship
Frequency	?	?	?	?
Frequency category	frequent	reasonably probable	remote	improbable
Category of effect	minor	minor	major, hazardous	catastrophic

The above code is still under the development and there are changeable numbers in the second last row according to the risk assessment provided. The proper safety code in the form presented in Table 2 or in the form of prescriptive rules should be prepared according to the data available from the DHDB data base. It should be taken into account that there is lack of risk assessment methods including the risk acceptance criteria for a few safety domains represented within the ISSEM method.

5. Computational model for ships safety estimation in critical conditions — modern numerical techniques

5.1. Logical structure of ISSEM design system

The structure of the ISSEM design system combines both the global and technical approaches described in Chapter 4. And the logical structure of the ISSEM design system is presented in Figure 6.

All the particulars of the ISSEM design system have been included into the author's D.Sc. thesis to be published in 1999. The most important features of the ISSEM system are as follows:

1. system is open;
2. system structure is hybrid–modular;
3. system has a common library of analytical and numerical methods;
4. system has a common library of application methods (direct geometry–based methods are preferable);
5. system should enable the analysis to be done at a few project stages.

5.2. Logical structure of ISSEM computational model. ISSEM DynamicalHydromechanic Data Base

The links between the global and technical approaches are incorporated by the computational model introduced in Figure 7.

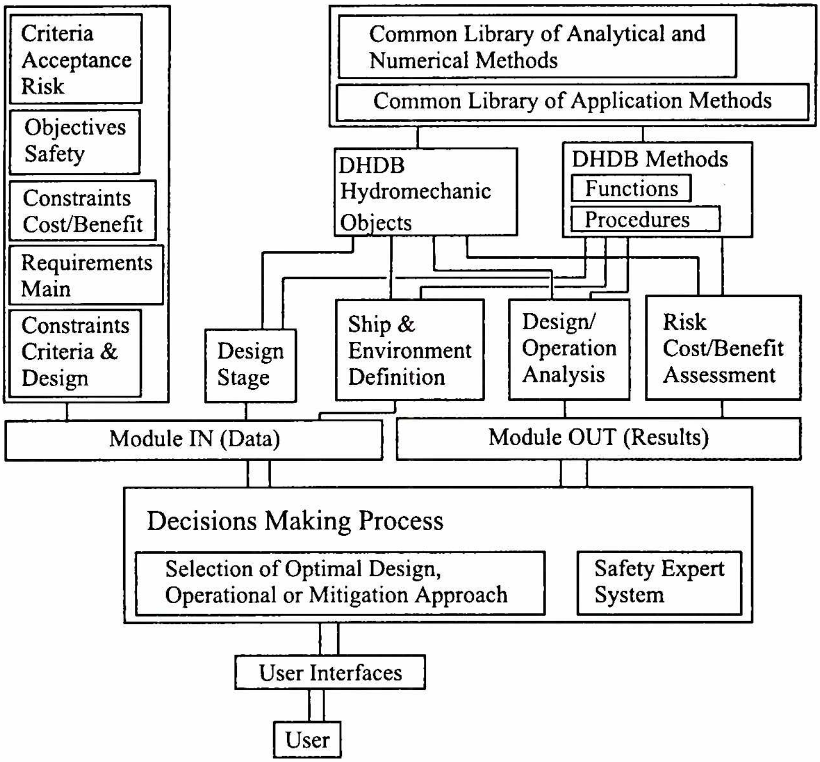


***Figure** 7. Logical structure of the ISSEM computational model.*

The computational model is based on the ISSEM DYNAMICAL HYDROMECHANIC DATA BASE (DHDB) concept and it is original. The basic information concerning the DHDB was published a few years ago when a computer program for the preliminary ship design of operational stability was discussed [33]. The structure of DHDB data base is presented in Figure 8.

The DHDB data base enables to provide the safety estimation when the ship hydromechanic characteristics can be obtained using either the hydronumerical calculations (direct methods), model tests results, results from the full scale trials, empirical and hydronumerical calculations (semi direct methods) or empirical calculations (indirect methods). Both the ship and environment are defined as hydromechanic objects described by a set of parameters. The safety domains ("Hydromechanic Analysis") are called the design methods using both the functions and procedures associated with solving particular hydromechanic problems. The "Risk Assessment" module includes the methods which combine both the "hydromechanic" and "risk assessment" functions and procedures. Currently this module applies a limited number of methods. The DHDB data base has a lot of advantages and a few disadvantages. In fact this needs another publication to be done on the DHDB data base concept details.

The main ISSEM requirements may be as follows: general requirements, IMO regulations, requirements of classification societies and requirements of

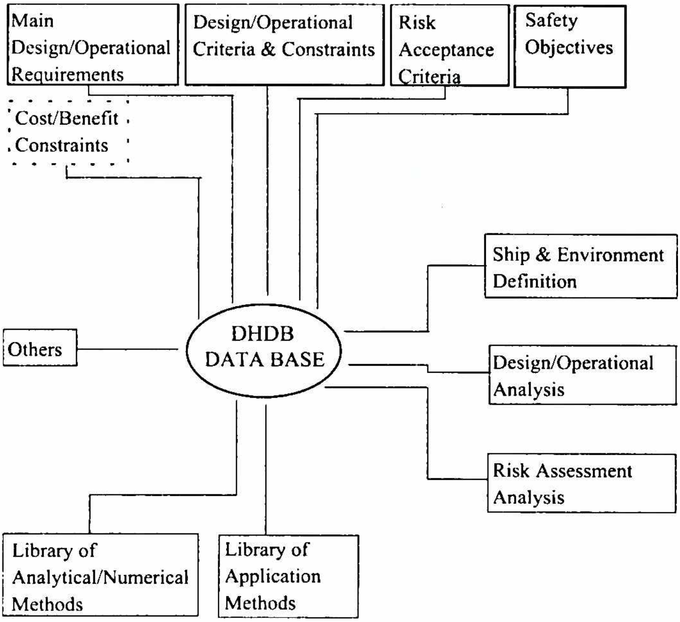


***Figure 8.** Structure of DHDB data base.*

conventions. The current set of requirements used by the ISSEM DHDB consists of the IMO regulations.

The ISSEM DHDB should include both the risk acceptance criteria, safety objectives, main requirements and design criteria and constraints. These are very important components of the computational model and they shall be discussed in another paper. The full range of problems associated with all the above mentioned is in the author's D.Sc. thesis which is to be published in 1999.

According to the risk assessment methods presented in Chapter 4.3 it is possible to present the ISSEM DHDB components in the form of the following examples.

Risk assessment for seakeeping

As the DHDB input file includes the following data:

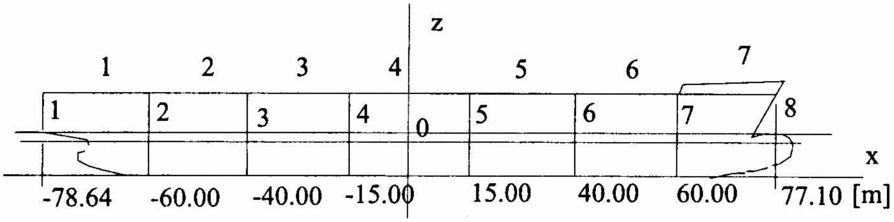
L [m] = 52.0 — ship length;
B [m] = 13.0 — ship breadth;
d [m] = 4.6 — ship draught;
$c_B = 0.532$ — ship block coefficient;
$c_{WL} = 0.74$ — ship waterline coefficient;
$c_M = 0.888$ — ship midship section coefficient;
ψ [rad] = 3.14 — course angle;
v [m/s] = 2.056 — heading speed;
$n_{AS} = 1$ — number of additional sections (>= 1);
GM [m] = 1.0 — ship metacentric height;
h_S [m] = 5.0 — significant wave height;
A_K [–] = 0.0 — relative area of bilge keels.

RISK ASSESSMENT FOR SURVIVABILITY
(Criteria: obtaining the maximum value A)

Ship parameters:

Ls = 153.50 m - subdivision length
Lbp = 148.00 m - length between perpendiculars
B = 24.00 m - breadth
H = 13.90 m - height
dl = 9.00 m - draught in full loading condition
d2 = 6.00 m - draught in ballast loading condition

Arrangement of internal spaces:



Risk assessment (* - the latest changes):

A. Preliminary arrangement of internal spaces (as presented in Figure 9'):

1. preliminary position of each bulkhead:
   -78.64, -60.00, -40.00, -15.00, 15.00, 40.00, 60.00, 77.10 - 6 bulkheads
2. risk assessment:
   4 iterations have been done and the final position of each bulkhead is as follows: -78.64, -60.00, -40.00, -16.69*, 15.00, 38.40*, 60.00, 77.10
3. data obtained A = { 0.6561, 0.7188, 0.8164, 0.8171 }

B. Partially fixed arrangement of internal spaces (bulkheads no. 2, 3 and 7) according to the classification rules (LR) and machinery arrangements:

1. preliminary position of each bulkhead:
   -78.64, -60.00, -35.20, -7.80, 15.00, 43.40, 64.20, 77.10
2. risk assessment: new positions of bulk.no. 4 (-9.63) and 6 (41.29)
3. data obtained A = { 0.60.52, 0.7268, 0.7953 }

C. Partially fixed arrangement of internal spaces (bulkheads no. 2, 3 and 8) as it is for the parent ship

1. preliminary position of each bulkhead:
   -78.64, -63.00, -40.20, -20.30, 8.30, 27.5, 43.20, 62.45, 77.10 - 7 bulk.
2. risk assessment:
   1st iteration - index A = 0.6694 (expert advice: bulk.4 move from position -20.30 to new position -20.99)
   2nd iteration - index A = 0.8219 , etc...
3. data obtained A = { 0.6694, 0.8219, 0.8225, 0.8278*, 0.8233 }

Figure 9. Risk assessment for survivability for a cargo ship.

The DHDB output file contains the following values for the K1 and K2 criteria:

K1 = 0.683
K2 = 1.088

obtained for the hull form data point as follows: x = 0.33 L, y = 0.33 B and z = 2 T.

If the K1 and K2 risk values are accepted, then there is no necessity to modify the design according to the possibilities presented in Figure 6. Of course, we can obtain all the intermediate results including both the wave description and ship motions, too.

Risk assessment for stability

When the reliability index is calculated according to the "First Order Second Moment" the probability of capsizing is as follows [37]:

$$P_C = 0.0965083$$

for the data mean values of the random variables:

$$A_1 = 91000 \text{ and } A_2 = 54000$$

The above results were achieved for the ship called Gillmer having the following characteristics:

displacement Δ = 15.000 [tons]
heeling moment (in flooding) = 30.000*cos(φ) [foot*tons]

6. Conclusions

The idea of the Integrated Ship Safety Estimation Method has been worked out. Currently, the method is a kind of Integrated Formal Safety Assessment (IFSA) semi risk–based method. It may be used on a case by case basis and for the rule development purposes. A few safety levels are introduced in the ISSEM method. And there is lack of the risk assessment algorithms for a few ship hydromechanic domains. Generally, both the probabilistic and deterministic safety measure techniques are used by the method. As the human factor is the cause of almost 80% of accidents at sea it should be taken into account, too. But there is still no method to incorporate this factor into the ISSEM method.

The above presented both the method and computational model have been used for investigating the new solutions regarding the ships safety from the damage stability and survivability point of view. Three unconventional arrangements of internal spaces for a simplified ro–ro type ship have been used. Both the full stability and risk assessment were done for each case. The preliminary results are very promising from the practical point of view and they should be shortly presented during the International HYDRONAV'99 Conference in September 1999.

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