The state of the art in modeling ship stability in waves

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THE STATE OF THE ART IN MODELING SHIP STABILITY IN WAVES

by

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ABSTRACT

In 1996, the 22nd ITTC formed a Specialist Committee on Ship Stability. There were two main mandates given to this committee. The first was to examine the techniques for carrying out model experiments used to investigate the capsize of intact and damaged ships and provide guidelines for carrying out these experiments. The second was to assess the methods available for numerical simulations of the capsize of intact and damaged ships.

This paper describes the findings of the committee so far, at the end of its second year of a three year term. The committee has prepared a summary of the state of art in the areas of numerical and physical modeling of intact and damaged ships. It has also circulated a questionnaire concerning the type of numerical methods used by ITTC member organizations for predicting the capsize of intact and damaged ships. Another major objective of the committee is to 'benchmark' codes against a standard hull form, for which there are well documented experiments. The hull form chosen was a container ship tested at Osaka University.

This paper provides a brief summary of the findings of the committee in each of the four subject areas and makes recommendations for standard model test methods for intact and damage capsize predictions. It also discusses the preliminary findings from the questionnaire.

INTRODUCTION

The basic purpose of studying capsizing is to establish prediction techniques which may be used by ship designers to create safe and seaworthy ships. In order to do this, we need a scientific understanding of the dynamic stability problem and in particular, how the forces in a capsize situation are influenced by wave and ship parameters. Research using scale models and realistic wave conditions combined with analytical work taught us a great deal about the nature of the capsize process. This understanding lead to the development of numerical simulations of the large amplitude motions of the ship in certain situations. It was observed that severe motions, control problems and capsizes occurred when the model encountered a wave group train of several steep, almost regular waves. This experimental observation suggested that the probability of capsize may be related to the probability of encountering a wave group with the characteristics necessary for a capsize. Early experimental work indicated that the three major types of capsize were low cycle resonance (parametric rolling), pure loss of stability and broaching to. Later research indicated additional types of capsizing, namely due to excitation by steep, breaking waves and foundering due to water ingress and flooding in general.

Physical experiments have long played an important role in assessing the safety of flooded ships, ro-ro ferries in particular. Early studies were in the form of simple attempts to establish stability limits based on stability parameters. These progressed to sophisticated measurements of water accumulating on the deck of the flooded ship. Numerical methods for studying flooded vessels are now as sophisticated as model experiments and the two methods combined make very powerful prediction techniques. The major difference between the capsize of an intact ship and a damaged ship is the length of time for it to occur. Intact ships typically capsize in a few wave encounters, whereas a flooded ship can take typically take twenty minutes. This has some effect on the methodology used to approach to the problem.

It is now possible to make reliable predictions of a ship capsize using either physical or numerical methods. Unlike the more established predictions of ship performance in calm water and in waves (seakeeping), there are no accepted standards for capsize predictions. The ITTC Specialist Committee on Ship Stability was formed in 1996 with two objectives. One was to examine the techniques for carrying out model tests to study capsizing of intact and damaged ships and the other was to provide guidelines for carrying out these tests. It was also instructed to assess the methods available for numerically simulating the capsize of an intact or damaged ship. This paper presents the results of the findings so far, at the end of the second year of the committee's work.

REVIEW OF NUMERICAL METHODS AVAILABLE FOR PREDICTING SHIP CAPSIZE

Roll angle is the primary measure of dynamic stability, but roll is strongly coupled to the other motions of the vessel. For this reason, it is impossible to have a comprehensive model of ship stability which does not include all six degrees of freedom. There are several different approaches used to predict the dynamic behaviour of a ship in waves. These can be generally classified as follows

1. Frequency domain solutions, linear or non-linear hydrodynamic models
2. Time domain solutions, linear or non-linear hydrodynamic models
3. Non-linear system dynamics approach to the Equations of Motion (application of chaos and bifurcation theory etc.)

The foundations of the methodology for the use of numerical models to evaluate the stability of intact and damaged ships and of floating structures in waves have been set in the early seventies by the work of Paulling et al (1974)*)*. The initial work, which included theoretical and numerical analysis and model tests concentrated on the capsizing of intact ships in astern seas. At a later stage, Paulling et al. addressed the dynamic stability problem of intact and damaged offshore rigs in waves. In their following work, the Berkley team extended their numerical procedure to cover ship motions and the capsizing of ships in stern quartering and arbitrary wave directions.

The mathematical problem formulation of the kinematics of a rigid 3D body in waves was exact and straightforward, following well-established concepts of aeronautics. The induced simplifications concerned the fluid dynamics and the interaction between the fluid and the structure. For example, two dimensional strip theory was used to calculate hydrodynamic coefficients for ships and a Morison's formula approach was used for slender offshore structures. This numerical procedure was later extended, by several authors, to include three-dimensional effects and the possibility of hull damage. A comprehensive list of references related to the stability of intact ships in waves is provided by de Kat et al (1994, 1998)

Time domain methods are generally the most widely applied methods for studying ship stability in waves. These techniques have the advantage of using a computer model with a direct relationship to the physical situation for ship geometry, wave conditions and vessel motions. They are also a logical extrapolation of linear, frequency domain programs for predicting ship motions. The most recent review of the numerical modeling of the stability of ships in waves, Papanikolaou (1997) and Zaraphonitis (1997), concluded that exact modeling of the fully nonlinear behaviour of ships in waves is, for the time being, beyond the range of existing mathematical models, for reasons which are discussed below.

The hydrodynamic forces on the ship can be separated into three types of flow. They are: potential (inviscid) flow, non-ideal flow (viscous flow, vortex shedding, etc.) and, in case of water ingress or flooding, water flow on open spaces (hydraulic bore models). Potential flow is amenable to different solution techniques (varying from simplified two dimensional linear theory to fully non-linear three dimensional theories). There are however significant limitations when dealing with unsteady viscous flow combined with a free surface. To circumvent this problem, all simulation methods for ship motion predictions in waves rely on empirical modeling of the viscous forces associated with the hull and appendages.

This means that in order to be able to make reasonable predictions of ship capsizing, the most common approach has been to develop hybrid methods. These are time domain models where part of the model is based on linear ship motion theory, but some non-linear effects are included. The non-linearities most commonly considered in the fluid forces are: Froude-Krylov forces and hydrostatic forces up to the instantaneous free surface. There are other non-linearities to consider when predicting the stability of ships in waves, namely viscous effects and higher order radiation and diffraction effects. The latter are mostly not accounted for by present numerical models.

Maneuvering and course keeping in waves has traditionally been separated from seakeeping predictions. The most typical approach is to combine unsteady motion predictions based on potential flow with the maneuvering predictions in calm water. A few methods use empirical data to address the coupling of motions, e.g. heel induced yaw moment.

The modeling of water on deck is the subject of ongoing research. Some simulation models attempt to account for the dynamic effects associated with fluid motion within the hull. The methods tend to be based on solving shallow water equations for a predetermined amount of water on the deck. The fluid movement within the hull can induce severe impact loads (sloshing) or can change the motions of the vessel, especially for small vessels with bulwarks. A considerable problem is the consistent treatment of the disturbed flow around the hull interacting with the flow on and off the deck.

A variety of models are nowadays in use for addressing the damage stability problem of ships in waves, particularly 6 degree of freedom models, Vassalos (1995, 1997), Papanikolaou (1997), and Huang (1996) and hybrid, quasi 2D approaches, as shown by Chang (1997). Both methods give satisfactory and useful results for practical applications. An in depth review of the literature on damage stability, focusing on the stability characteristics of Ro-Ro passenger ships is given by Vassalos (1994).

The modeling of the flooding process remains a critical issue, Vassalos (1997). Among other issues to be reconsidered, both experimentally and theoretically, are the possible shapes of the damage opening. Six different shaped openings were considered (experi-mentally) and the "worst" damage opening, from the point of view of causing a capsize, appears to be a "wedge" type profile opening, with wider upper part, allowing more water to flood in, and narrower lower part, obstructing the flooding out of the same amount of water. The application of semi-empirical coefficients are relevant in this process. These results might revive the discussion about the definition of the damage opening according to the relevant IMO regulation.

A further issue, to be considered in the mathematical modeling of the flooding process is the consideration of flood water dynamics, including sloshing effects. It is understood, that present models use a quasi-static approach, in considering the effect of floodwater, by assuming the internal water surface to be horizontal and parallel to the external one and by considering the heel moment effect of the internal water mass. This assumption might work properly at the final stage of capsizing, however, in several cases, depending on the relative magnitude of the flood water and the internal water depth, internal resonance and interactions with the ship dynamics will produce additional dynamic effects, which should affect the ship motions and the vessel's tendency to capsize.

Some evidence on this aspect and a methodology of approach is given in the papers by Papanikolaou (1997). De Kat (1996) illustrates the consequence of neglecting sloshing dynamics on ship response in beam waves. Other approaches, suggested by Vassalos, were to build up a comprehensive database through a systematic series of model experiments or to employ CFD computational techniques, along with the best simulation model. Finally Chang (1997) employed a shallow-water equation approach in connection with Glimm's method to obtain a solution for the case of low fill depth compared to the tank width, however without an improved model for the water in-flow and outflow through the damage opening, the method gives good results only for small heel (less than about 25 degrees).

FACTORS TO CONSIDER WHEN SELECTING A NUMERICAL MODEL

Given below are some factors to consider when reviewing or selecting a numerical method for predicting a ship capsize.

The Environment

Waves are obviously the main factor influencing the dynamic stability of a ship so the selection of the modeling method is important. The hydrodynamic properties of the waves are commonly defined by a potential (harmonic) function, which is sinusoidal for small amplitude waves. This has many advantages in relation to its mathematical properties, but it does not represent properly observed wave shapes of steep water waves typical of those encountered in the capsize of an intact ship. For these waves, nonlinear third (or higher) order Stokes waves are a better representation requiring more complex mathematical techniques when solving the related ship-wave interaction problem and the equations of motion. Deep water waves are acceptable for many applications, but shallow water increases the steepness of the waves and may be important in specific problems such as broaching or capsizing in surf. Wave directionality is usually ignored.

Wind and current are typically ignored in ship stability numerical prediction models, though their inclusion appears straightforward. Obviously wind can induce forces and moments in the equations of motion of the ship, and current direction relative to the incident waves will have an effect on their shape and impact on the ship. Wind and current may be most relevant in the case of a drifting or damaged ship.

The Hull

Most models of ship stability in waves have focused on relatively simple mono-hull ships. However when selecting a method, care should be taken to ensure that the following elements are included in the modeling process.

From a dynamic stability perspective the ship consists of the hull, the superstructure, deck and deck structures, the propulsion system and the appendages (including the rudder). It should also include any openings in the deck or bulwarks and the cargo. Motion control systems should also be included.

Some typical simplifying assumptions related to the model of the hull are;

- Ignoring the hull and superstructure above the waterline,
- Ignoring deck openings,
- Cargo remains stationary
- Including rudder and control surfaces as part of the hydrodynamic coefficients for the hull
- Propulsion system assumed to be constant RPM and uniform loading.

Auto-Pilot

The auto-pilot method used in the computer program should be given careful consideration. The simplest method of all is to assume that the ship maintains a constant heading and the rudder has no influence on ship motions. In reality the movement of the rudder induces motions in the ship and these should be included in the simulation, especially in stern and stern quartering waves. The first level of complexity to be include in the simulation model is a simple PID controller that responds to yaw angle and yaw rate. This is a relatively simple controller to construct and tune for simulations and for model experiments. However, it is not necessarily representative of the actual auto-pilot used on a ship. This can be remedied by including an actual ship auto-pilot in the control system as a black box. A steering control algorithm provides information on the desired rudder angles at any particular instant as part of its feedback system.

The actual rudder angle will depend on the response of the rudder actuator, which has physical limitations on its performance, in both amplitude and rate of change. Few simulation models take this into account.

REVIEW OF EXPERIMENT TECHNIQUES FOR PREDICTING SHIP CAPSIZE

In parallel with the development of numerical methods for predicting a ship capsize, experiment techniques around the same problem have been developed. Physical experiments provide;

- visualization of the physical conditions,
- research tools for parametric studies on ship safety and
- data with which to validate predictions made by computer programs.

The somewhat surprising trend for model experiments studying ship capsizing has been that there are relatively few ship types studied. The focus for capsizing intact ships has been on container ships and fishing boats. Both types of hull form have been included in IMO guidelines for masters to avoid dangerous situations at sea.

Model experiments on flooded ships have almost exclusively been related to ro-ro ferries. Initial studies were to provide margins of safety for flooded hydrostatic stability to ensure that the ship survived in waves. Later studies took a slightly more sophisticated approach, in that they tried to understand the physics of the flooding process. Finally, model experiments were accepted as an alternative to prescriptive rules, following the capsize of the Estonia in 1994.

During the period studied, the nature of the model testing has become more sophisticated, with large amounts of data being recorded during experiments. This data typically includes time histories of model motions, wave height, relative motion between model and waves, video of the model including water flow on and off the deck, speed and track of the model. The outfit of the model has challenged the design of instrumentation, because of the constraints small models, large motions and the need for waterproofing.

RECOMMENDED STANDARDS FOR SHIP CAPSIZING MODEL EXPERIMENTS

Part of the work of the ITTC Specialist Committee on Ship Stability has been to review the literature on ship capsizing model experiments and prepare recommendations for carrying out these demanding experiments. This section describes the minimum recommended standards for carrying out experiments to study ship capsizing. They apply to both intact and flooded ships.

Model construction must result in a geometric representation of the following components of the ship;

- external hull shape
- appendages (rudders, bilge keels, propulsion appendages, etc.)

and where relevant;

- superstructure (external), deck, deck structures, bulwarks and drainage holes

In the case of the model of a flooded ship, the following additional parameters should be modeled;

- superstructure (internal, allowing for simplification of construction details)
- internal structures limiting flow inside the hull (such as casings or bulkheads)
- subdivision and flooding under the main deck
- collision damage opening (if required) should have sharp edges
- permeability and amount of cross flooding should be as realistic as possible

Minimum model scale should be 1:40 for models of flooded ships.

Models must be ballasted to the correct values of

- displacement and trim
- vertical centre of gravity
- radii of gyration (pitch in air, roll in air)

Inclining tests must be carried out to determine the following parameters

- GM (intact model)
- GM (flooded model, if required)
- GZ as a function of heel angle (port and starboard, intact and flooded if required)

A standard procedure still has to be developed for carrying out measurements of righting moment against heel angle for large heel angles.

For computer code validation purposes, experiments should be carried out in operational conditions (low to moderate wave heights) and extreme conditions (moderate to high wave heights). In the case of intact models with propulsion and steering systems, turning circles and zig-zag experiments should also be carried out. Other experiments which are necessary for validating computer codes are roll decay tests in calm water (with and without forward speed) and rudder induced roll oscillations in calm water. It is also desirable to carry out forced oscillation experiments, captive or partially captive experiments in waves and wind tunnel experiments on the topsides.

Measurements must be made of the motions of the model in six degrees of freedom, the track and speed of the model, rudder motion, forces and moments, propeller rotation rate (and/or thrust), wave height in the vicinity of the model and relative motion between the model and the water surface (fore and aft). Good quality video records of the experiments is also important. In the case of a self-propelled model the auto-pilot equation and its coefficients must also be recorded.

The following additional factors should be considered for models of flooded ships. The model must be free to drift under the action of the waves, and not restrained. In the case when the survivability of a specific ship design is being considered, ten separate wave trains, all with the same nominal significant waveheight, but different random phases, should be used. Wind gustiness need not be modeled until further research shows that this is necessary.

FUTURE WORK

The above review of the state of the art was a paper study, reviewing published literature. In order to capture the latest developments, the Specialist Committee on Ship Stability circulated a questionnaire to all members of the ITTC. The objective was to ascertain a detailed description of the computer programs currently in use to study ship stability in waves. At the time of writing, not all the replies have been received, but preliminary analysis shows the following results.

From this survey we found the following results. Fifteen programs have been described, from eight countries[1].

Maximum degrees of freedom	Number of replies
6	5
5	1
4	2
3	6
2	0
1	1

Solution techniques	
Non-linear	3
Linear/non-linear hybrid	9
Linear	2
N/A	1
3-dimensional hydrodynamics	5
2-dimensional hydrodynamics	8
N/A	2

[1] At time of writing replies have been received from Canada (1), China (1), Finland (1), Japan (5), Netherlands (1), Romania (1), UK (2) and USA (3)

The distribution of capsize modes which were covered by each program are given below.

Loss of stability in wave crest	8
Broaching	6
Parametric rolling	7
Steep, breaking waves	1
Foundering due to water ingress	6
Other	3

A more detailed analysis of the survey is underway, and will be part of the committee's final report to the ITTC. However, from these results, it was found that the most common option for studying ship stability in waves was using two dimensional hydrodynamics with linear/non-linear hybrid methodologies. Some specialist codes were described for single applications, such as capsize of damaged ships, or studying stability in beam waves using non-linear system dynamics methods.

The Specialist Committee on Ship Stability also asked ITTC members if they were willing to validate their computer programs for predicting ship behaviour in waves against as standard set of model experiments. The candidate ship is a container ship, tested in Japan and described by Hamamoto, (1995, 1996), for which a wide range of ship stability, wave conditions and capsize modes were studied. We feel that this will be an important step in truly assessing the state of the art of the numerical techniques.

CONCLUSIONS

Numerical modeling of the stability of ships in waves continues to be a challenging process for scientists and software developers. The demands on the software algorithms have increased from a relatively simple simulation technique of intact and damage body motions in waves to the requirement for sophisticated design tools enabling the simulation of the influence of alternative design measures on the survivability of intact and damage ships in seaways. It is understood, that reliable and efficient software tools can greatly facilitate the physical model testing procedure and ultimately provide efficient and economic design solutions.

It has been discussed that along with model testing, mathematical and physical simulation can be a valid alternative to prescriptive rules for demonstrating the survivability of a specific ship design. In order for this approach to be legitimate, both numerical models and physical testing facilities must develop and adopt an acceptable procedure. At present there are some areas of uncertainty for both numerical and physical modeling. Systematic evaluation of the proposed methods by properly defined benchmark examples can lead to final conclusions and possibly influence current IMO regulations.

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