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Mathematical Modelling of Motions and Damaged Stability of Ro-Ro Ships in the Intermediate Stages of Flooding

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Abstract

It is generally recognized that the phenomenon of a "rapid capsize" during the intermediate stages of flooding may represent a potentially dangerous situation to a ship. This is particularly true for a roll-on/roll-off (Ro-Ro) ferry sustaining a "high energy" collision due to the lack of subdivision on the car deck. In order to analyse the associated safety problems, a mathematical model has been developed with the aim to describe the actual motion behaviour and the associated residual stability of a ship in the time domain after sustaining a collision damage. This prediction instrument has been validated to a great extent by model experiments for a pontoon with cross-duct connected wing tanks and a typical ferry with a few different damage orifices and in addition various compartment configurations.
An outline of the mathematical model and the corresponding computer program is presented, discussing in particular the dynamics involved during the ingress of water with due emphasis on the importance of the instantaneous roll angle and the effect of subdivision arrangements on the distribution of floodwater. Further the results of a study on the parameters involved, such as the configuration of the damage orifice, and systematic calculations carried out for a number of existing Ro-Ro passenger ships yielded a number of conclusions relevant to the inherent safety of such vessels after a high energy collision. These conclusions address the validity of calculations for regulatory purposes traditionally based on quasi-static considerations, the actual occurring angle of heel in relation to possible shift of cargo and the effectiveness of several subdivision alternatives.

1 Introduction

Due to a great number of capsizes accidents involving Ro-Ro ships there was a growing concern about the safety of this type of ship. This development has led to an intensified effort in the field of scientific research and safety legislation.
It was generally recognized that the phenomenon of rapid capsizing during the

intermediate stages of flooding represents a potentially dangerous situation to a Ro-Ro ship after a collision damage. This view is also reflected in previous studies and reference is made to e.g. Braund (1978), Spouge (1985) and Boltwood (1988) for a more comprehensive analysis of the different aspects under consideration.
Because of this reason a research project was initiated with the aim to develop an accurate numerical prediction model of the phenomenon. The present paper gives an account of the development and validation of this prediction instrument with the capability to identify dangerous situations.

2 Mathematical Model

The basic assumptions, inherent to the computer program, are that the ship is floating with zero speed in still water and that the damage opening is in no way obstructed by the ramming vessel. This means that the ship motions due to wave excitation are ignored and likewise sloshing of floodwater has been disregarded. In this way the flooding mechanism is more explicitly reflected.
For the initial condition at $t = 0$ it has been arbitrarily assumed that the damaged ship is motionless.
There are three main areas that are relevant in the technical sense to be distinguished for the structure of the mathematical model describing the ship behaviour due to sudden water ingress:

- hydrostatic particulars of the ship,
- flow characteristics of floodwater and
- motion response of the ship in the time domain.

In order to give an outline of the mathematical model, the above-indicated elements will be discussed in more detail in the following sections.

2.1 Motion Response in the Time Domain

The ship motions are calculated using the equations of motion for a mass-spring system. The coupled motions roll, sway and yaw have been used whereas the dynamics of the other motions have been ignored.
For a harmonic excitation of a linear system, the equations of motion may be written as follows (using a generalized vector notation):

$$\sum_{j=2,4,6} \left(A_{k,j} + a_{k,j}\right) \cdot \ddot{h}_j + b_{k,j} \cdot \dot{h}_j + c_{k,j} \cdot h_j = X_k$$

$$\left(k = 2,4,6\right)$$

where:

$A_{k,j}$ Mass or moment of inertia of ship
$a_{k,j}$ Hydrodynamic mass or hydrodynamic moment of inertia
$b_{k,j}$ Hydrodynamic damping coefficient
$c_{k,j}$ Spring coefficient
$h_{k,j}$ Displacement of harmonic oscillation in direction j
X_k Harmonic exciting force or moment in direction k

The linear hydrodynamic coefficients in the frequency domain have been calculated with a program based on potential flow theory using the so-called 'strip theory' method. For the determination of the hydrodynamic deep water two-dimensional coefficients of ship-like cross sections, these sections are conformably mapped to the unit circle by the so-called two-parameter (i.e. sectional half breadth to draught ratio and sectional area coefficient) Lewis transformation.
However the computer program offers a choice of other conformal mapping methods in association with an alternative potential theory to be used for any desired water depth.
In order to carry out accurate ship motion response calculations in the time domain,

non-linearities and memory functions have to be included in the equations of motion as follows:

- non-linear contributions to be included in the right-hand side of the equation of motion additional to the external force/moment terms,
- non-linear viscous roll damping to be calculated according to the empirical method of Ikeda, Himeno and Tanaka (1978) and
- convolution integrals have to be applied in order to use hydrodynamic data, which are available in the frequency domain only, in transient calculations.

For this purpose the memory functions can be represented by the "Cummins equations" according to Cummins (1962) and Ogilvie (1964), resulting in $a_{k,j}(t) = a_{k,j}(w)$ for $w \to \infty$ and a damping term written in the form of a convolution integral consisting of the factors $\dot{h}_j(t)$, the j-th velocity component at time t, and a retardation function $K_{k,j}(t)$ which reads as:

$$K_{k,j}(t) = \frac{2}{p} \int_0^\infty b_{k,j}(w) \cdot \cos(wt) \cdot dw$$

2.2 Flow Characteristics of Floodwater

The flow characteristics of floodwater are completely described by the application of two fundamental theorems:

- theorem of Bernoulli and
- law of Boyle - Gay Lussac.

Application of Bernoulli's theorem and taking into account the linear distribution of the hydrostatic water pressure over the height of the orifice leads to the following expression for the flux ΔQ of floodwater through any horizontal strip:

$$\Delta Q = \Delta A \cdot \sqrt{\frac{2 \cdot \Delta P}{r \cdot C_D}}$$

where:

ΔA	Sectional area of flow strip considered
ΔP	Pressure difference across the strip
r	Density of sea water
C_D	Pressure loss ('drag') coefficient

The value of the pressure loss coefficient C_D for cross-flooding openings may be found in literature and reference is made to e.g. Blevins (1984), Ireland (1988) and ICMO Resolution A.266 (1973).
In this regard it should be noted that the speed reduction factor F as defined in IMCO Resolution A.266 (1973) is related to C_D as:

$$F = \frac{1}{\sqrt{1 + C_D}}$$

In a similar way the application of the law of Boyle - Gay Lussac in addition to the theorem of Bernoulli leads to an expression for the flow rate of air.

2.3 Hydrostatic Particulars of Ship

The restoring moment is determined by the following expression:

$$c_{ff} \cdot f = rg\nabla \cdot \left(\overline{KN_f} - \overline{KG}\right) \cdot \sin f$$

where:

f	Angle of heel
∇	Ship's volume of displacement
$\overline{KN_f}$	Metacentric height above keel
$\overline{KG}$	Distance of ship's vertical center of gravity above keel

It should be noted that the other spring terms for sway and yaw are non-existent (i.e. zero).
The heeling moment M_f is determined by a summation of the inclining moments caused by the weight of floodwater in each compartment:

$$M_f = \sum_i g \cdot v_i \cdot \left(- y_i \cos f + z_i \sin f - \overline{KG} \sin f \right)$$

where:

g	Specific gravity of sea water
v_i	Volume of floodwater in compartment i
y_i	Transverse position of center of gravity of v_i from center line
z_i	Vertical distance of center of gravity of v_i above keel

Use has been made of a conventional 'ship hydrostatics' software package modified in such a way to fit this particular application.
On the basis of the defined geometry of hull form and compartmentation arrangement, the following information is available:

- intact stability characteristics by means of so-called cross curves $\left(\overline{KN_f} \cdot \sin f\right)$ as function of the instantaneous ship draught, trim and angle of heel and
- actual location of the center of gravity (x_i, y_i and z_i) of the instantaneous volume of floodwater v_i in each compartment i considered in the flooding process.

3 Computer Program

The applied calculation method has been laid down in a computer program called DYNING, which is the acronym of the expression 'DYNamic INGress' referring to the dynamic response of a ship due to a sudden ingress of water.
An interface has been established between the main program with two preprocessing programs generating the following information:

- hydrodynamic coefficients of the equations of motion as described in section 2.1 of the paper of which all algorithms are described in detail by Journée (1991), and
- hydrostatic data and tank data as described in Section 2.3 of the paper.

The 2nd order differential equations of motion are solved by a Runge-Kutta time integration.
The output of the computer program yields information, presented as a function of time, on the following parameters:

- amount of sea water in all compartments liable to flooding in the damage case under consideration,
- draught, trim and roll angle and
- residual righting lever curve
$$\overline{GZ_f} = \left(\overline{KN_f} - \overline{KG}\right) \cdot \sin f - \frac{M_f}{rg\nabla}$$
at any arbitrary time instant during the intermediate stages of flooding assuming the amount of floodwater in each compartment fixed to the amount present at that time instant.

The effect of permeability, vent-openings, tween-decks and major obstructions, such as a propulsion unit in the engine room, are accounted for in the mathematical model in order to reflect the actual flooding process as closely as possible.

4 Experimental Validation

The calculation model has been validated by model experiments on a rectangular pontoon with cross-duct connected wing tanks. A comprehensive discussion about the results above has been presented by Vredeveldt and Journée (1991).
Further model experiments have been carried out on a representative ferry, which are to be reported in TNO report (1994). For this purpose several subdivision arrangements and areas of damage orifices were taken into consideration.

5 Test Calculations and Parameter Study

In order to gain experience with the practical application of the computer program as an instrument, a parameter study and extensive test calculations on several existing Ro-Ro passenger ships have been carried out.

5.1 Parameter Study

The main purpose of the parameter study is a sensitivity analysis of the most critical parameters in the mathematical model. The following parameters have been subject of a systematic investigation:

- damage orifice area: variation of width of hole,
- initial mass moment of inertia of ship: variation of $\pm 25\%$,
- drag coefficient for internal flow: variation of $\pm 50\%$,
- area of air vent: variation of $\pm 50\%$ and
- presence of bilge keels: variation of roll damping.

It turns out that the results, although not unexpected, are to a great extent affected by variations of damage orifice area as demonstrated in Figure 1 in terms of a time simulation of the roll angle.

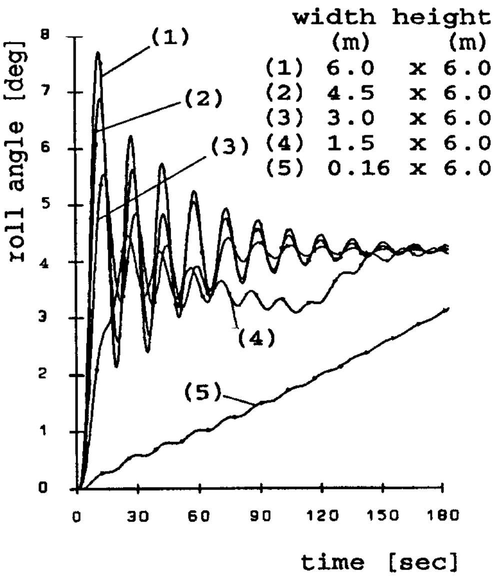

Figure 1 Time Simulation of Rolling Angle for Various Damage Orifice Areas

The other parameters, within the range indicated above, have however only a very minor effect on the maximum roll angle and the conclusion seems justified that the mathematical model is not very dependent on a high accuracy of these parameters.

In addition to this parameter study, an investigation was carried out into the SOLAS-criteria in the final stage of flooding. For the damage scenario under consideration (non)-submergence of the margin line was by far the overriding criterion due to the fact that a high degree of asymmetry is present in this particular (non-SOLAS) one-compartment damage case. A decrease of $\overline{KG}_{max}$ or draught (see Figure 2) shows respectively a substantial reduction (due to an excessive high $\overline{GM}$-value) or a slight increase (due to a decrease in displacement) of the maximum roll angle which is defined as the first roll amplitude in time.

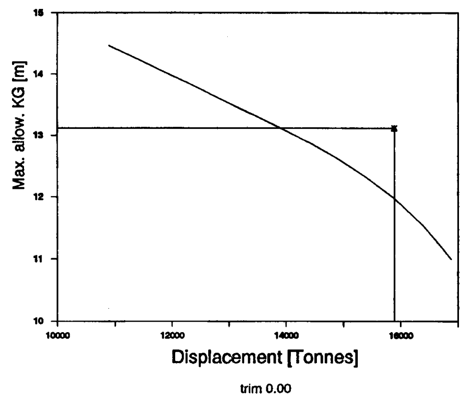

Figure 2 Maximum Allowable KG as Function of Displacement Based on the Criterion of Margin Line Submersion

It should be noted that the residual stability in the intermediate stages of flooding does not present a safety problem because the car deck is not submerged during the intermediate stages of flooding.

5.2 Test Calculations

For the purpose of providing a basis of comparison one damage orifice configuration, as given in Figure 3, has consistently been used throughout all test calculations.

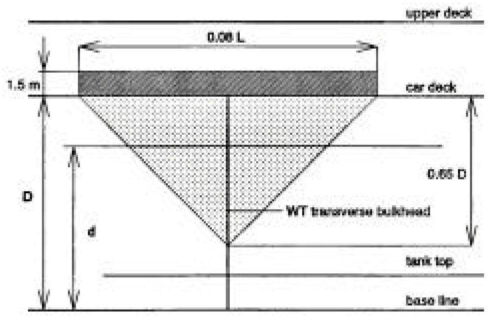

Figure 3 Configuration of Damage Orifice for the Test Calculations

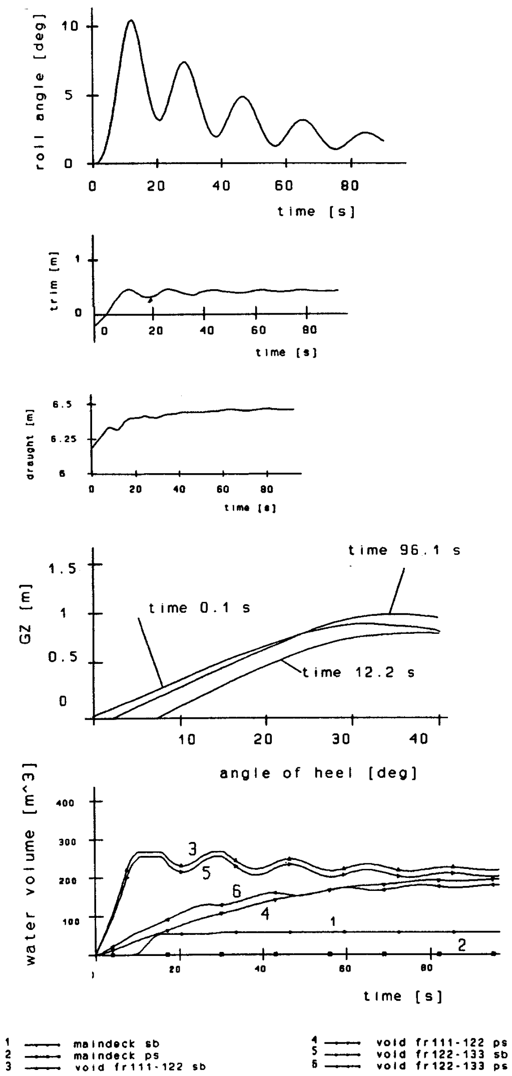

Figure 4 Time Simulation of the Behaviour of a Pre-SOLAS Ro-Ro Passenger Ship Following a Two-Compartment Damage of Cross-Duct Connected Wing Tanks

The results of a two-compartment damage of cross-duct connected wing tanks of a pre-SOLAS 90 Ro-Ro passenger ship are presented in Figure 4. The ship does survive this particular damage case although shipping of water occurs at the first roll amplitude. This minor amount of water remains trapped on the car deck due to the trim developed. Due to a relative high time constant for the flow through the cross duct it may be concluded that the equalizing arrangement does not significantly affect the first overshoot of the roll angle.

The result (in terms of a time history of the roll angle) of a two-compartment damage of wing compartments of a one-compartment standard SOLAS 90 Ro-Ro passenger ship (intended for the carriage of lorry drivers) is presented in Figure 5.

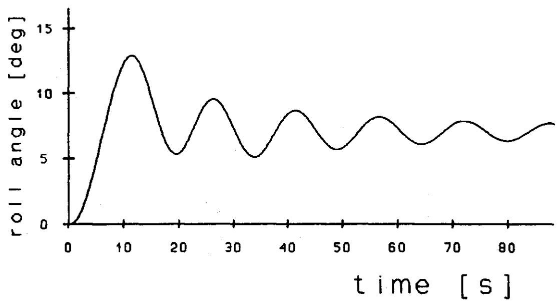

Figure 5 Time Simulation of Roll Angle of a SOLAS 90 Ro-Ro Passenger Ship (One-Compartment Standard) Following a Two-Compartment Damage of Void Spaces in the Side

Likewise the ship does survive the assumed damage scenario although a greater angle of heel occurs in the final stage of flooding due to the absence of a cross-flooding arrangement.

The results of a two-compartment damage of engine rooms of a pre- SOLAS 90 Ro-

Ro passenger ship are presented in Figure 6.

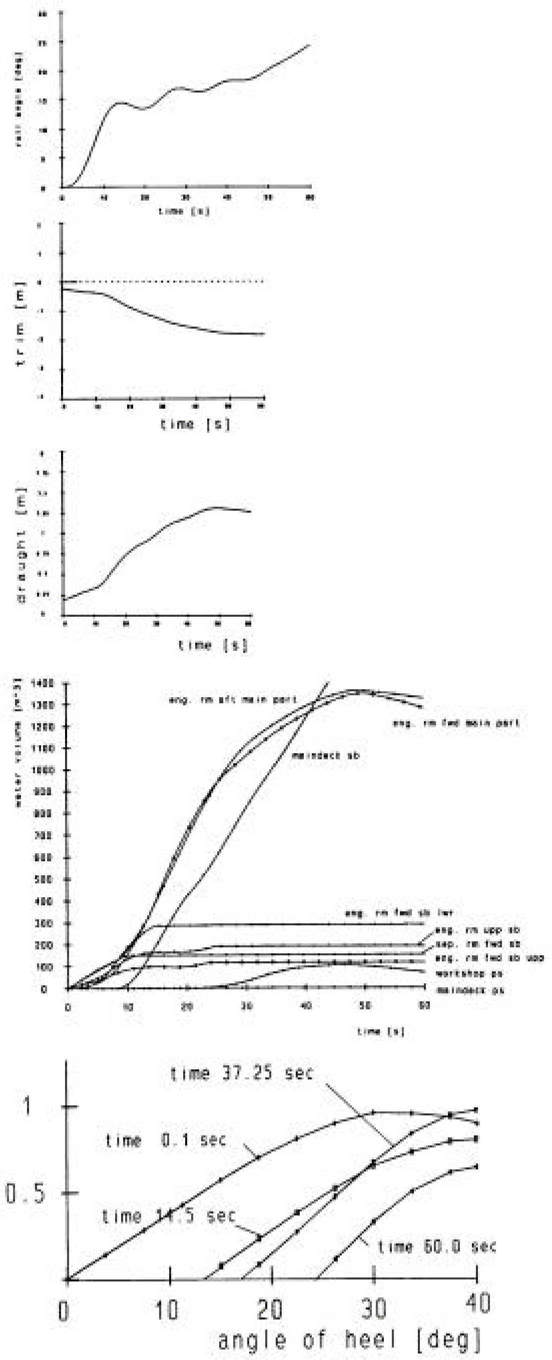

Figure 6 Time Simulation of the Behaviour of a Pre-SOLAS 90 Ro-Ro Passenger Ship Following a Two-Compartment Damage of Engine Rooms

In this particular damage case the effects of a tween-deck and the main propulsion unit have been included in the model. It is obvious from Figure 6 that the ship does not survive this particular damage case because shipping of water occurs at the first roll amplitude and the heeling moment due to floodwater in the engine rooms sub-compartments is so large that flooding of the car deck continues subsequently developing an ever-increasing list. It should be noted that the ship survives a one-compartment damage to only one engine room.

The result (in terms of a time history of the roll angle) of a two-compartment damage of engine rooms of a SOLAS 90 Ro-Ro passenger ship (one-compartment standard) for various effects of modeling is presented in Figure 7.

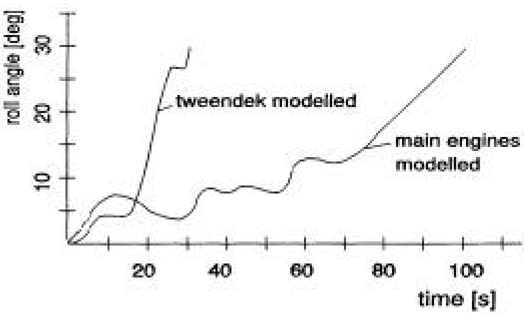

Figure 7 Time Simulation of Roll Angle of a SOLAS 90 Ro-Ro Passenger Ship (One-Compartment Standard) Following a Two-Compartment Damage of Engine Rooms for Various Effects of Modeling

Likewise the ship does not survive the assumed damage scenario although flooding of the car deck occurs at the second roll amplitude. This means that the distribution of floodwater in the engine room and the associated heeling moment is one major effect inducing a rapid capsizing. In this respect it should be observed from Figure 7 that the presence of a tween-deck is a deteriorating factor, whereas the presence of a major obstruction is beneficial to some extent.

6 Discussion and Conclusions

A mathematical model has been developed to describe the actual motion behaviour and the associated residual stability of a ship in the time domain after sustaining a collision damage. An outline of the mathematical model is presented in Section 2 of the paper. The calculation method has been made effective by means of a computer program as described in Section 3 of the paper. Validation experiments, as indicated in Section 4 of the paper, have been carried out showing that the accuracy of the calculation method is such that the computer program may well be used as a prediction instrument.

The main conclusion of the study is that calculations carried out in accordance with existing international legislation do not represent a realistic picture of the actual flooding process of a damaged Ro-Ro ship after a high-energy collision.

It has been demonstrated that the sudden ingress of water in the transient stages initiates and increases the heeling moment generated by floodwater. This is particularly true for Ro-Ro ships, which usually have a center of gravity above keel in the range 1.5-2.0 times full load draught d.

The lever of the heeling moment at $t = 0$ reads as follows:

$$\frac{\left(\overline{KG}_{\max} - d + z_A\right) \cdot z_A \cdot A_t}{\nabla}$$

where:

- ∇ Volume of displacement
- z_A Distance from center of hydrostatic pressure of A_t to water line
- A_t Submerged area of the damage orifice which by nature is time-dependent and increases in a progressive manner during the first quarter of the first roll cycle assuming that the damage extends above the car deck.

In this very elementary analytical expression the value of $\overline{KG}_{\max}/d$ is very critical for e.g. car deck submergence at the first roll amplitude.

The test calculations, reported in Section 5.2 of the paper, have shown that the application of a longitudinal subdivision may be very beneficial to avoid the rapid capsizing phenomenon.

The compartment configuration, which is unfavorable from this point of view, is characterized by voluminous compartments without a longitudinal subdivision to bound the heeling moment of floodwater. The effect becomes even more pronounced by the existence of tween-decks below the waterline, a high ship's center of gravity relative to the waterline and obviously the occurrence of a relative low value of freeboard and/or $\overline{GM}$ in the intact condition.

Although not accounted for in the mathematical model it may be expected that a rapid capsize is preceded by shifting of cargo due to the occurrence of a substantial list f or some time. The rapid capsizing process as such is a fatality and for this reason it is desirable to have pertinent knowledge on the probability of occurrence of a high-energy collision.

For the purpose of this study a realistic damage orifice with a rather large area has been used, however in this respect statistical information for the assessment of the size of the damage orifice, either deterministic or in the probabilistic sense, is indispensable.

7 Acknowledgement

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