



SURvivability Evaluation

Predicting a ship is in dangerous condition by observing its motion

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Project Manager:
Peter Grundevik

Author:
Heng Ran
heng.ran@sspa.se
031 772 9045

SURE

The overall aim of the project is to increase the knowledge of dangerous ship conditions, how to keep away from them and how to maneuver the ship in the best way under these circumstances. In the recently finished project 'Safety & Cargo System' a first prototype of a decision support system of a ship in danger has been designed. Some new approaches were also suggested in the Decision Support System of the DESSO ROPAX in the DESSO project. The objective now is to use the fundamental parts of those systems as well as to revise and develop the system further. The expected result of the project is that the gained knowledge and the developed decision support system will give an improved support for the bridge operators onboard, but rescue and ship operator office actors may also use it on shore.

SSPA Sweden AB

SSPA Sweden AB

Peter Grundevik
Vice President
Head of SSPA Research

Heng Ran
Project Manager
SSPA Research Department

SSPA SWEDEN AB – YOUR MARITIME SOLUTION PARTNER

HEAD OFFICE: P.O. Box 24001 · SE-400 22 Göteborg · Sweden · Tel: +46 (0)31-772 90 00 · Fax: +46 (0)31-772 91 24
VISITING ADDRESS: Chalmers Tvärgata 10 · SE-412 58 Göteborg · Sweden

BRANCH OFFICE: Fiskargatan 8 · SE-116 20 Stockholm · Sweden · Tel: +46 (0)31-772 90 00 · Fax: +46 (0)8-31 15 43
INTERNET: www.sspa.se · E-MAIL: postmaster@sspa.se · VAT NO: SE556224191801

Summary and recommendations

Severe wind, wave conditions bring difficulties to ship manoeuvring. Especially under damaged conditions, water ingress from the damaged openings could result in capsizing. Former study has been carried out by SSPA in developing a system, which predicts the ship's risk of capsizing by transducer measurement of ingress fluid volumes. This first prototype of a decision support system is expensive to be applied on board.

The aim of this study is to develop an alternative decision support system by analysing ship motions. A sloshing model is developed based on SSPA manoeuvring and seakeeping software SEAMAN. Instead of model test, simulation is used as the method of the study. Developing simulation techniques makes it possible to avoid the complicity of model test procedure design. The use of simulation method makes it to be specific about the operating conditions and resulted ship motions.

With the sloshing model developed, simulations are carried out for ship in different headings and damaged conditions. By analysing ship motions, dangerous conditions could be identified as follows.

1. For intact ship, the heave and roll motions increase in beam sea.
2. For damaged ship in head sea, the heave and pitch motions are obvious. Damaged ship in Beam Sea, is the most dangerous condition, where heave, pitch motions are significantly larger than normal, while roll motion is slightly smaller.

For further study, other external conditions should be considered. During sea trials, strong wind condition will increase the complicity of ship motions, so as to influence water ingress. The stability of damaged ship when dragging by tug boats is another interesting topic to look into.

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1 Introduction

Damaged ship stability and manoeuvrability are important for life and cargo safety onboard a ship.

When ship is travelling at sea, detecting ship damage and water ingress in time is very helpful in controlling dangerous situation and increase ship stability. However, in some cases for example MS Estonia, it is difficult to detect ship damage by unusual sound or sudden motion of the ship. The delay in detection increases probability to capsize.

In all ship laboratories, manoeuvring and seakeeping tests for damaged ship don't belong to conventional test. Both ship model and the testing procedure require specific design. The design procedure and testing process are time consuming and expensive.

Summarizing the requirement of both sea travelling and laboratory test, the aim of this study is to investigate if damage induced water ingress is predictable by analyzing ship motions. SSPA indoor manoeuvring and seakeeping software SEAMAN is further developed and used for simulations in this study.

Sloshing phenomenon is selected as a focusing topic in software development. SEAMAN, which uses stripe theory model, provides a simulation speed faster than real time. In order to retain the simulation speed for industrial application, when modelling sloshing, the acceleration ratio method is selected.

The study is carried out in the following process.

1. Mathematical modelling of sloshing
2. Constructing ship model with compartments
3. Simulations for intact ship and damaged ship in different sea states
4. Comparison and analysis

2 Ship data

The ship being selected for this study is MS Skåne, which owned by Stenaline. It is a RoPax vessel operating on the Trelleborg-Rostock route. SSPA has done various studies about MS. Skåne, including manoeuvring and sea keeping tests. Table 2.1 shows the main dimensions of the ship.

Ship parameter	Dimension	Magnitude
Length over all	m	200.2
Length between perpendiculars	m	186.2
Beam	m	29
Draught aft	m	6.24
Draught fore	m	6.16
Displacement	m ³	23 063
LCG rel. midship	m	-5.49
Number of propellers	set	2
Propeller rotation speed at max speed	rpm	150
Propeller diameter	m	4.5
Number of rudders	set	2
Area per rudder	m ²	25
Max rudder turning angle	°	35.0
Rudder turning speed	°/s	4
Lateral wind area	m ²	4650
Transverse wind area	m ²	812

Table 1 Main dimensions of MS Skåne¹

MS Skåne was built in 1998. The design speed of the ship is 21 knots. It is equipped with four MAN B&W 48/60L8 diesel engines, which provide 28 960 kW engine power. It can take 600 passengers and 500 cars on board. Its lane capacity is 1110m. Figure 2.1 shows a picture of MS Skåne.



Figure 1 MS Skåne pictureⁱⁱ

3 Math model

The sloshing math model was built on SSPA Maneuvering and seakeeping software SEAMAN. In SEAMAN, the internal flooding model assumed the water ingress has a horizontal free surface. In order to better represent sloshing phenomenon, acceleration ratio method is adopted to calculate the slope of flooded water free surface.

3.1 Principles and assumption

The most up-to-date methods for simulating sloshing are CFD (computational fluid dynamics), VOF (volume of fluid), MAC (marker and cell). However, the complication in model construction and high requirement on computation cost became two major disadvantages for implementing such methods in SEAMAN code.

Acceleration ratio method is adopted to calculate the slope of flooded water free surface. The free surface of water ingress is assumed to change moderate. Certain assumptions are made when applying the method.

- The free surface of water ingress is one even plane.
- The slope of free surface in ship transverse plane is identical along the longitudinal axis of the ship.
- Free surface slope changes from one value to another without delay or accumulation, i.e. inertia is excluded in the model; water surface could change its shape instantly.
- The shape of the tanks is convex quadrilateral. The top and bottom of the tank are parallel.

The principle of acceleration ratio method is based on fluid static pressure. In plane yoz (as shown in Figure 2), the pressure P at certain location below water surface is a function of the location, i.e. $P(y,z)$.

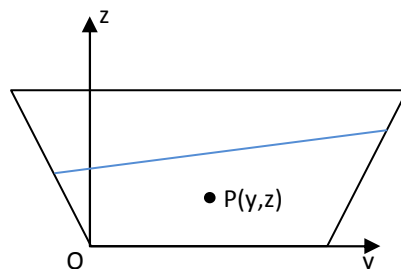


Figure 2

Coordinate system of flooded tank

$$dP(y, z) = \frac{\partial P(y, z)}{\partial y} \cdot dy + \frac{\partial P(y, z)}{\partial z} \cdot dz \quad \text{Equation 1}$$

The total force acting on a fluid particle of volume is due to pressure and gravity. According to Robert W. Fox (1985, p.75)ⁱⁱⁱ, in rectangular coordinates the component equations are

$$-\frac{\partial p}{\partial y} + \rho \cdot g_y = \rho \cdot a_y \quad y \text{ direction} \quad \text{Equation 2}$$

$$-\frac{\partial p}{\partial z} + \rho \cdot g_z = \rho \cdot a_z \quad z \text{ direction} \quad \text{Equation 3}$$

On water surface

$$dP(y, z) = 0 \quad \text{Equation 4}$$

Substituting equation 2, 3, and 4 into Equation 1, will derive

$$\text{Free surface slope} = \frac{dz}{dy} = \frac{-a_y}{g + a_z} \quad \text{Equation 5}$$

3.2 Classification

Based on the tank geometry, volume of water ingress, and free surface slope, sloshing phenomenon is classified. Each situation is modelled separately. Table 2 summarizes all situations. The slopes k_{fs} and $k_{diagonal}$, the volumes V_{water} , V_{limit1} , and V_{limit2} are illustrated in Figure 3. **Error! Reference source not found.** shows each case graphically.

Free surface slope sign	Free surface slope compare with tank diagonal slope	volume	Case number
$k_{fs} \geq 0$	$ k_{fs} \leq k_{diagonal} $	$V_{water} \leq V_{limit1}$	1
		$V_{limit1} \leq V_{water} \leq V_{limit2}$	2
		$V_{water} \geq V_{limit2}$	3
	$ k_{fs} > k_{diagonal} $	$V_{water} \leq V_{limit1}$	4
		$V_{limit1} \leq V_{water} \leq V_{limit2}$	5
		$V_{water} \geq V_{limit2}$	6
$k_{fs} < 0$	$ k_{fs} \leq k_{diagonal} $	$V_{water} \leq V_{limit1}$	7
		$V_{limit1} \leq V_{water} \leq V_{limit2}$	8
		$V_{water} \geq V_{limit2}$	9
	$ k_{fs} > k_{diagonal} $	$V_{water} \leq V_{limit1}$	10
		$V_{limit1} \leq V_{water} \leq V_{limit2}$	11
		$V_{water} \geq V_{limit2}$	12

Table 2 Classification

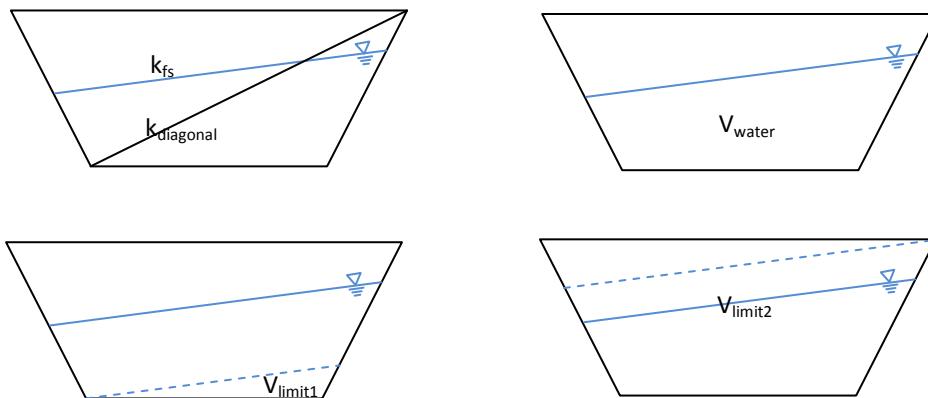


Figure 3 k, V illustration

3.3 Inflowed water centre of gravity

When calculating the centre of gravity of inflowed water, a three step process is followed.

- Step 1: Calculate ship transverse and vertical acceleration at tank centre.
- Step 2: Using acceleration ratio method to calculate free surface slope. Compute the coordinates of intersection points (free surface and tank wall) in tank fixed coordinate system.
- Step 3: Derive water centre of gravity using the coordinates of intersection points and tank corner points.

Among these steps, problems in step 2 are the most complicated to solve. Based on coordinates of tank corner points, line functions for tank walls are derived.

- Line 1: $z = k_1 \cdot y + b_1$
- Line 2: $z = k_2 \cdot y + b_2$
- Line 3: $z = k_3 \cdot y + b_3$
- Line 4: $z = k_4 \cdot y + b_4$

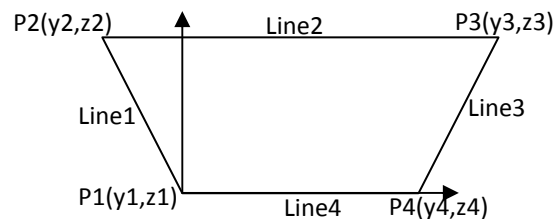
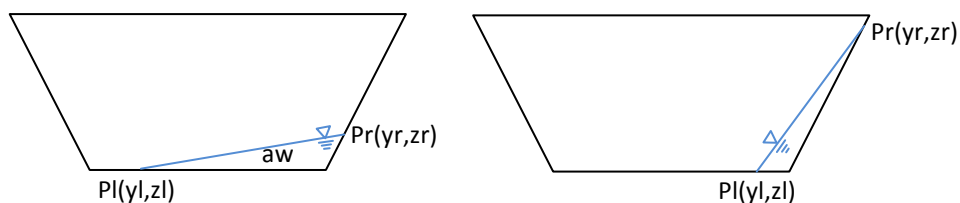


Figure 4 Tank wall line functions and corner points

To calculate intersection point coordinates, equations are composed by line functions and water volume. Detailed algorithms are explained in the following sections.

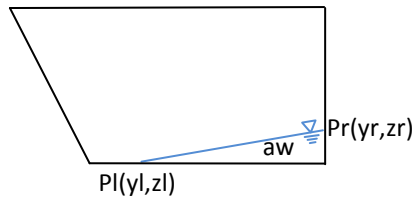
3.3.1 Case 1 and 4



Equations

$$\begin{cases} z_l = 0.0 \\ z_r = k \cdot y_r + b_3 \\ z_r = k \cdot y_l + b \\ z_l = k \cdot y_l + b \\ 0.5 \cdot (y_l \cdot z_r + y_r \cdot z_l + y_4 \cdot z_l - y_4 \cdot z_r - y_r \cdot z_l - y_l \cdot z_4) = a_w \end{cases}$$

Unknowns: y_l, z_l, y_r, z_r, b



Equations

$$\begin{cases} z_l = 0.0 \\ y_r = y_4 \\ 0.5 \cdot (z_r - z_l)^2 / k = a_w \\ y_l = y_4 - (z_r - z_l) / k \end{cases}$$

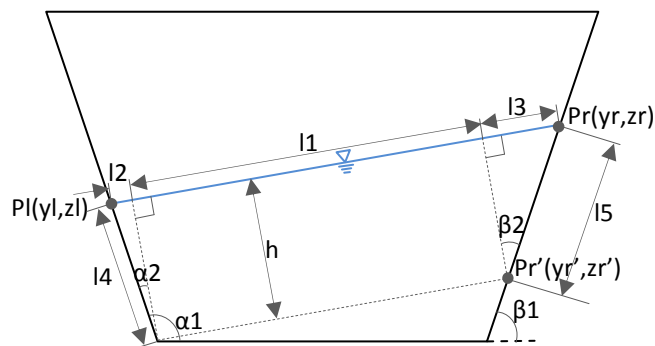
Unknowns: y_l, z_l, y_r, z_r

Centre of gravity

Transverse centre of gravity = $(y_l + y_r + y_4) / 3$

Vertical centre of gravity = $(z_l + z_r + z_4) / 3$

3.3.2 Case 2



Equations:

$$\left\{ \begin{array}{l} \alpha_1 = \text{atan}(k_1) \\ \beta_1 = \text{atan}(k_3) \\ \alpha_2 = |\text{atan}(k_1) - \text{atan}(-1/k)| \\ \beta_2 = |\text{atan}(k_3) - \text{atan}(-1/k)| \\ l_2 = h \cdot \tan(\alpha_2) \\ l_3 = h \cdot \tan(\beta_2) \\ l_1 = \text{sqrt}((y_{r'} - y_1)^2 + (z_{r'} - z_1)^2) \\ l_1 \cdot h + 0.5 \cdot (l_2 + l_3) \cdot h = a_w - 0.5 \cdot y_4 \cdot z_{r'} \end{array} \right.$$

Unknowns: $h, l_1, l_2, l_3, y_{r'}, z_{r'}$

$$\left\{ \begin{array}{l} h/l_4 = \cos(\alpha_2) \\ y_l = l_4 \cdot \sin(\alpha_1) \\ z_l = l_4 \cdot \cos(\alpha_1) \\ h/l_5 = \cos(\beta_2) \\ y_r = y_{r'} + l_5 \cdot \sin(\beta_1) \\ z_r = z_{r'} + l_5 \cdot \cos(\beta_1) \end{array} \right.$$

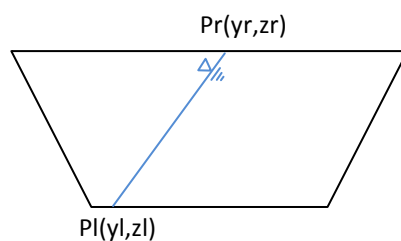
Unknowns: $l_4, l_5, y_l, z_l, y_r, z_r$

Centre of gravity

Transverse centre of gravity = $((y_l + y_1 + y_4)/3 \cdot \text{Area}_{\Delta P_1 P_4 P_l} + (y_l + y_r + y_4)/3 \cdot \text{Area}_{\Delta P_r P_4 P_l}) / a_w$

Vertical centre of gravity = $((z_l + z_1 + z_4)/3 \cdot \text{Area}_{\Delta P_1 P_4 P_l} + (z_l + z_r + z_4)/3 \cdot \text{Area}_{\Delta P_r P_4 P_l}) / a_w$

3.3.3 Case 5



Equations:

$$\begin{cases} z_r = z_2 \\ z_l = z_1 \\ z_l = k \cdot y_l + b \\ z_r = k \cdot y_r + b \\ (y_3 - y_r + y_4 - y_l) z_2 / 2 = a_w \end{cases}$$

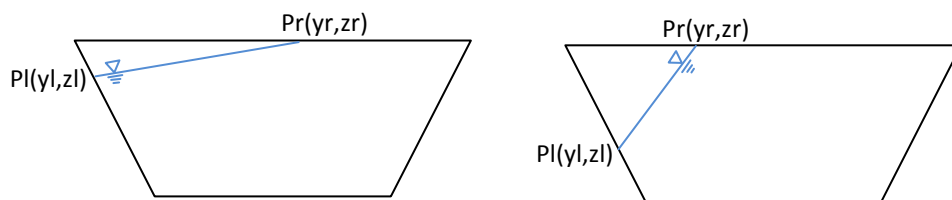
Unknowns: y_l , y_r , z_l , z_r

Centre of gravity

$$\text{Transverse centre of gravity} = ((y_r + y_3 + y_4) / 3 \cdot \text{Area}_{\Delta_{PrP3P4}} + (y_l + y_r + y_4) / 3 \cdot \text{Area}_{\Delta_{PlPrP4}}) / a_w$$

$$\text{Vertical centre of gravity} = ((z_r + z_3 + z_4) / 3 \cdot \text{Area}_{\Delta_{PrP3P4}} + (z_l + z_r + z_4) / 3 \cdot \text{Area}_{\Delta_{PlPrP4}}) / a_w$$

3.3.4 Case 3 and 6



Equations:

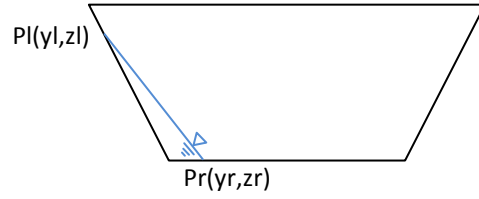
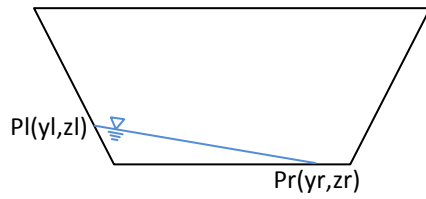
$$\begin{cases} z_r = z_2 \\ z_l = k_1 \cdot y_l + b_1 \\ z_r = k \cdot y_r + b \\ z_l = k \cdot y_l + b \\ a_{\text{Total}} = (y_3 - y_2 + y_4 - y_1) z_2 / 2 \\ 0.5 \cdot (y_l \cdot z_r + y_r \cdot z_2 + y_2 \cdot z_l - y_2 \cdot z_r - y_r \cdot z_l - y_l \cdot z_2) = a_{\text{Total}} - a_w \end{cases}$$

Centre of gravity

$$\text{Transverse centre of gravity} = ((y_l + y_1 + y_4) / 3 \cdot \text{Area}_{\Delta_{PlP1P4}} + (y_l + y_r + y_4) / 3 \cdot \text{Area}_{\Delta_{PlPrP4}} + (y_r + y_3 + y_4) / 3 \cdot \text{Area}_{\Delta_{PrP3P4}}) / a_w$$

$$\text{Vertical centre of gravity} = ((z_l + z_1 + z_4) / 3 \cdot \text{Area}_{\Delta_{PlP1P4}} + (z_l + z_r + z_4) / 3 \cdot \text{Area}_{\Delta_{PlPrP4}} + (z_r + z_3 + z_4) / 3 \cdot \text{Area}_{\Delta_{PrP3P4}}) / a_w$$

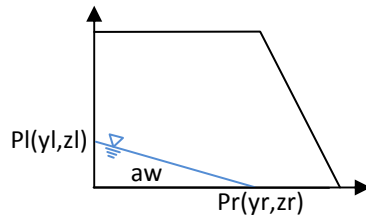
3.3.5 Case 7 and 10



Equations

$$\left\{ \begin{array}{l} z_r = 0.0 \\ z_l = k \cdot y_l + b_1 \\ z_r = k \cdot y_r + b \\ z_l = k \cdot y_l + b \\ 0.5 \cdot (y_l \cdot z_r + y_r \cdot z_l + y_1 \cdot z_l - y_1 \cdot z_r - y_r \cdot z_l - y_l \cdot z_1) = a_w \end{array} \right.$$

Unknowns: y_l, z_l, y_r, z_r, b



Equations:

$$\left\{ \begin{array}{l} z_r = 0.0 \\ y_l = y_1 \\ 0.5 \cdot (z_r - z_l)^2 / |k| = a_w \\ y_r = y_1 + (z_l - z_r) / k \end{array} \right.$$

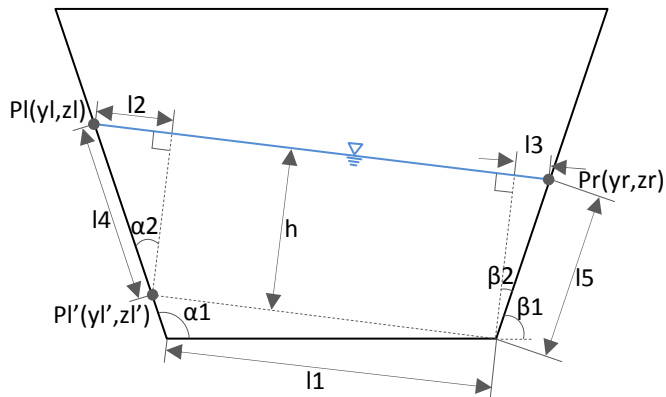
Unknowns: y_l, z_l, y_r, z_r

Centre of gravity

Transverse centre of gravity = $(y_l + y_r + y_1) / 3$

Vertical centre of gravity = $(z_l + z_r + z_1) / 3$

3.3.6 Case 8



Equations:

$$\left\{ \begin{array}{l} \alpha_1 = \text{atan}(k_1) \\ \beta_1 = \text{atan}(k_3) \\ \alpha_2 = |\text{atan}(k_1) - \text{atan}(-1/k)| \\ \beta_2 = |\text{atan}(k_3) - \text{atan}(-1/k)| \\ l_2 = h \cdot \tan(\alpha_2) \\ l_3 = h \cdot \tan(\beta_2) \\ l_1 = \text{sqrt}((y_l' - y_4)^2 + (z_l' - z_4)^2) \\ l_1 \cdot h + 0.5 \cdot (l_2 + l_3) \cdot h = a_w - 0.5 \cdot y_4 \cdot z_l' \end{array} \right.$$

Unknowns: h, l1, l2, l3, yl', zl'

$$\left\{ \begin{array}{l} h/l_5 = \cos(\beta_2) \\ y_r = l_5 \cdot \sin(\alpha_1) \\ z_r = l_5 \cdot \cos(\alpha_1) \\ h/l_4 = \cos(\alpha_2) \\ y_l = y_l' + l_4 \cdot \sin(\beta_1) \\ z_l = z_l' + l_4 \cdot \cos(\beta_1) \end{array} \right.$$

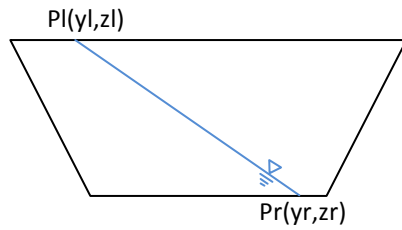
Unknowns: l4, l5, yl, zl, yr, zr

Centre of gravity

$$\text{Transverse centre of gravity} = ((y_l + y_1 + y_4)/3 \cdot \text{Area}_{\Delta P_1 P_4 P_l} + (y_l + y_r + y_4)/3 \cdot \text{Area}_{\Delta P_r P_4 P_l}) / a_w$$

$$\text{Vertical centre of gravity} = ((z_l + z_1 + z_4)/3 \cdot \text{Area}_{\Delta P_1 P_4 P_l} + (z_l + z_r + z_4)/3 \cdot \text{Area}_{\Delta P_r P_4 P_l}) / a_w$$

3.3.7 Case 11



Equations:

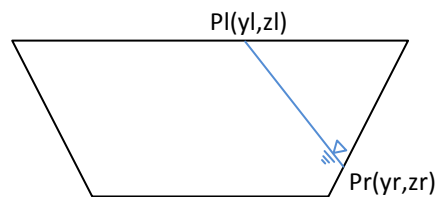
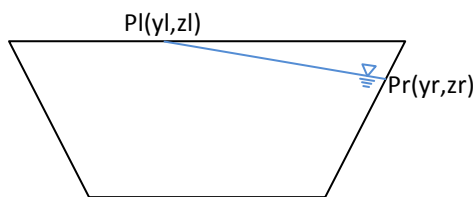
$$\left\{ \begin{array}{l} z_r = z_1 \\ z_l = z_2 \\ z_l = k \cdot y_l + b \\ z_r = k \cdot y_r + b \\ (y_l - y_2 + y_r - y_1) z_2 / 2 = aw \end{array} \right.$$

Centre of gravity

Transverse centre of gravity = $((y_l + y_r + y_1) / 3 \cdot \text{Area}_{\Delta P_1 P_r P_1} + (y_l + y_1 + y_2) / 3 \cdot \text{Area}_{\Delta P_1 P_1 P_2}) / aw$

Vertical centre of gravity = $((z_l + z_r + z_1) / 3 \cdot \text{Area}_{\Delta P_1 P_r P_1} + (z_l + z_1 + z_2) / 3 \cdot \text{Area}_{\Delta P_1 P_1 P_2}) / aw$

3.3.8 Case 9 and 12



Equations:

$$\left\{ \begin{array}{l} z_l = z_2 \\ z_r = k_3 \cdot y_r + b_3 \\ z_r = k \cdot y_r + b \\ z_l = k \cdot y_l + b \\ a_{\text{Total}} = (y_3 - y_2 + y_4 - y_1) z_2 / 2 \\ 0.5 \cdot (y_l \cdot z_r + y_r \cdot z_3 + y_3 \cdot z_l - y_3 \cdot z_r - y_r \cdot z_l - y_l \cdot z_3) = a_{\text{Total}} - a_w \end{array} \right.$$

Centre of gravity

Transverse centre of gravity = $((y_l + y_1 + y_2) / 3 \cdot \text{Area}_{\text{PIP1P2}} + (y_l + y_r + y_1) / 3 \cdot \text{Area}_{\text{PIPrP1}} + (y_r + y_1 + y_2) / 3 \cdot \text{Area}_{\text{PrP1P2}}) / a_w$

Vertical centre of gravity = $((z_l + z_1 + z_2) / 3 \cdot \text{Area}_{\text{PIP1P2}} + (z_l + z_r + z_1) / 3 \cdot \text{Area}_{\text{PIPrP1}} + (z_r + z_1 + z_2) / 3 \cdot \text{Area}_{\text{PrP1P2}}) / a_w$

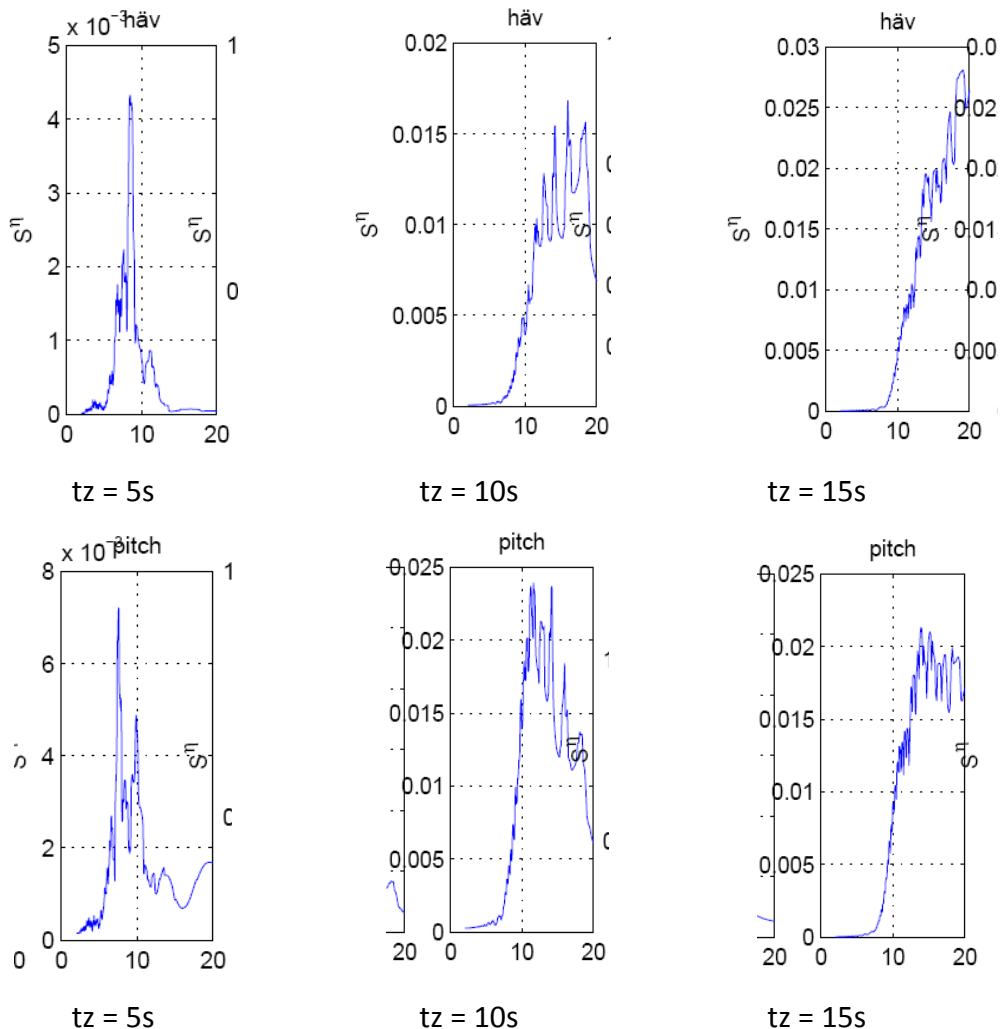
4 Result analysis

Dangerous situation could occur both at intact and damaged conditions. Simulations are carried out for intact ship in moderate wave, intact ship in violent wave and damaged ship in wave. The time series motions are processed with Fast Fourier Transformation. The energy of motion on each degree of freedom is plotted against wave frequency. The plots are demonstrated and compared in the following sections.

4.1 Moderate wave versus dangerous wave

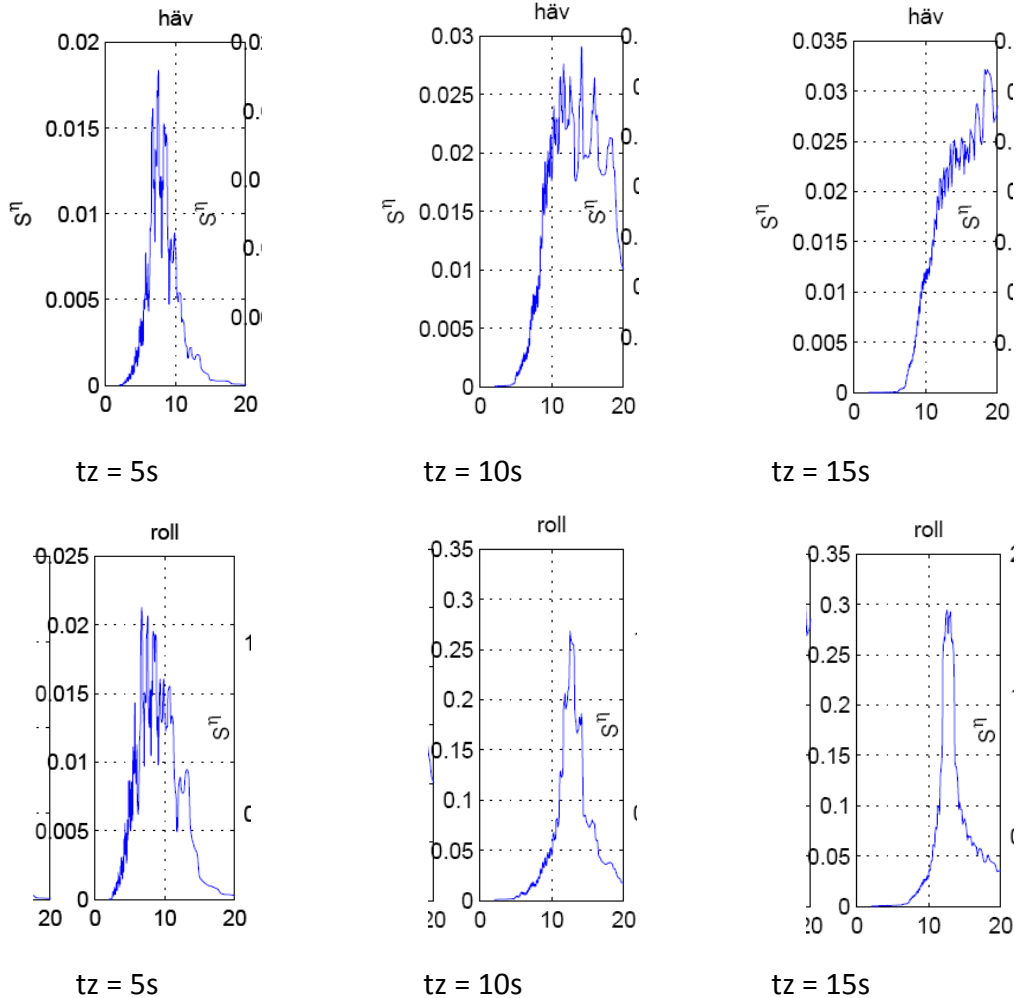
Wave direction and wave period affects ship motions in all degrees of freedom. From maneuvering point of view, heave, roll and pitch are three most important motions which indicate whether a ship is in danger.

4.1.1 Wave period influence on heave and pitch in head sea



In head sea condition, heave motion is significantly larger when wave period is larger. When the wave length is close to or higher than twice ship length, ship will be floating on wave slope. The increase of heave and pitch motion is captured by simulation.

4.1.2 Wave period influence on heave and roll in Beam Sea

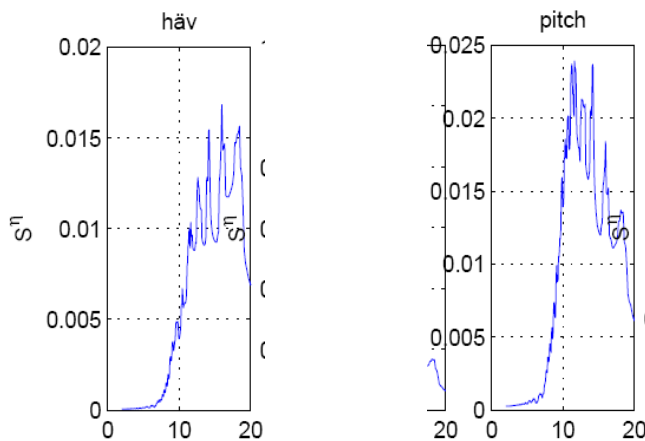


Comparing to head sea condition, heave and pitch motions are larger in beam sea for both zero crossing periods. The increase in motion is more obvious at lower wave period. It is widely known, ships should try to avoid Beam Sea, so as to avoid large motions induced by wave. By analysing resulted ship motions, the phenomenon is captured.

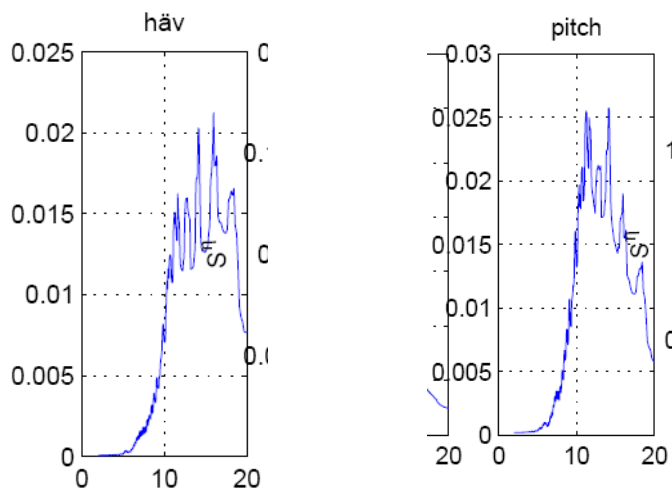
4.2 Intact ship versus damaged ship

A group of simulation is carried out for damaged ship with two compartments water ingression. These two compartments are located on bow side. In both headings, the heave and pitch motions are increased under damaged case. However, the roll motion is smaller. This might be induced by ingress water free surface effect. Therefore, the decrease of motion in roll together with increase of motion in other degrees of freedom is a warning sign for ship damage.

4.2.1 Intact and damaged ship in head sea

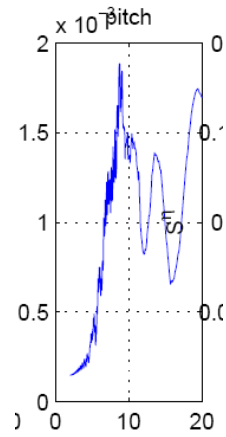
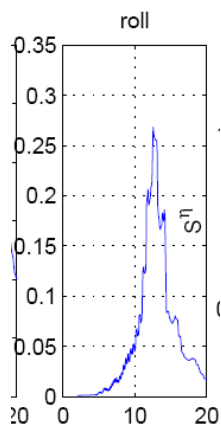


Intact ship $t_z = 10s$

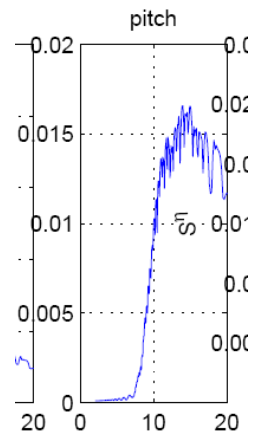
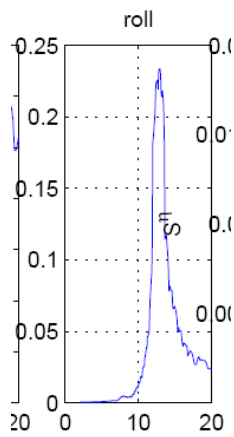


Damaged ship $t_z = 10s$

4.2.2 Intact and damaged ship in beam sea



Intact ship $t_z = 10s$



Damaged ship $t_z = 10s$

5 Conclusions

With the simple sloshing model developed, simulations are carried out for ship in different headings and damaged conditions. By analysing ship motions, dangerous conditions could be identified as follows.

1. For intact ship, the heave and roll motions increase in beam sea.
2. For damaged ship in head sea, the heave and pitch motions are obvious. Damaged ship in Beam Sea, is the most dangerous condition, where heave, pitch motions are significantly larger than normal, while roll motion is slightly smaller.

For further study, other external conditions should be considered. During sea trials, strong wind condition will increase the complicity of ship motions, so as to influence water ingression. The stability of damaged ship when dragging by tug boats is another interesting topic to look into.

6 Reference

ⁱ Data source from SSPA manoeuvring model test data base and Stenaline's home page
www.stenaline.se

ⁱⁱ Picture source: Klubb Maritim.(2008) M/S SKÅNE [online]. Farsta: Micke Asklander. Available from:
<http://www.faktaomfartyg.se/skane_1998.htm> [Accessed 16 April 2008]

ⁱⁱⁱ Robert W. Fox, Alan T. McDonald, (1985) Introduction to Fluid Mechanics. 3rd ed. John Wiley & Sons, Inc.