Gian Carlo Matheus Torres

6th EMship cycle: October 2015 – February 2017

Master Thesis

Development of formulas allowing to predict hydrodynamic responses of inland vessels operated within the range of navigation 0.6 ≤ Hs ≤ 2.0

Supervisor: **Professor Maciej Taczała** West Pomeranian University of Technology, Szczecin, Poland.
Internship tutor: Nzengu Wa Nzengu. : Bureau Veritas Inland Navigation, Antwerp, Belgium.
Reviewer: Professor Robert Bronsart, University of Rostock, Rostock, Germany.

Szczecin, February 2017

Summary

1. Introduction

- When designing a vessel, it is of interest for a naval architect to rely on an adequate **‘design response’** to sea waves: an extreme dynamic load, displacement or acceleration with a small probability that will be exceeded.

- It serves as an **adequate input** to undertake **FE model analysis**, so structure strength and intrinsic behaviour can be studied accordingly.

- These loads coming from the sea **must** accurately **be predicted by classification societies** and should not be exceeded during the lifetime in operation of a given vessel.

1. Introduction

- This study was carried out accounting for **only fully loaded conditions** to create a database of extreme values:
  - ➢ Linear potential flow theory is used on **Hydrostar code** (belonging to Bureau Veritas); based on:
    - ✓ Frequency-domain scheme for simulations of rigid hulls in extreme waves,
    - ✓ Boundary element methods,
    - ✓ 3D Rankine Panel method theory,
    - ✓ Impossed forwad speed V = 10 kn.
- Belgian coastal Wave Spectrum, provided by the institute of Oceanography located in Ostend, was used.

2. Objectives

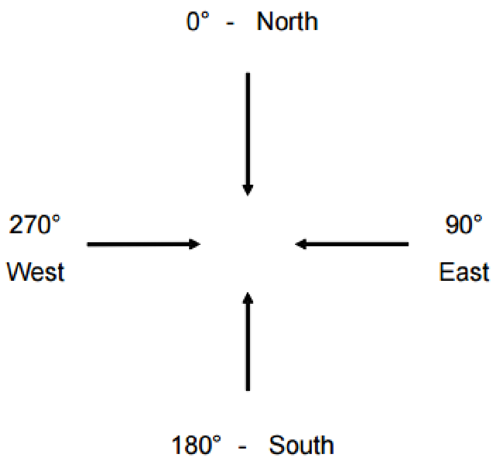
I) Obtaining long-term responses for a set of 46 vessels simulated under fully loaded conditions, based on linear potential flow theory. It includes amplitudes, velocities and accelerations acting on and about the centre of gravity and the relative elevation, shear forces and bending moments exerting influence on specific ship-hull locations.

II) Propose empirical formulas accounting for the main motions and accelerations parameters, including relative motions.

III) Correct the empirical formulas taking into account nonlinear effects and forward speed effects.

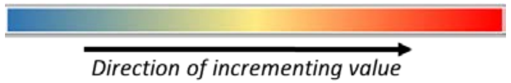
3. Excitation

Belgian Coastal **Scatter Diagram** up to Hs = 2.0 m



Waves direction's reference.

Hs / Tp	3.00	3.50	4.00	4.50	5.00	5.50	6.00	6.50	7.00	7.50	8.00	8.50	9.00	SUM
0.20	0	0	6.0	57.5	173.9	129.3	52.2	24.9	10.6	0.8	0	0	0	455.1
0.30	0	3.0	78.6	189.7	305.4	293.3	142.9	75.6	6.8	2.3	0	0	0	1097.7
0.40	0	9.8	80.9	257.8	383.3	316.8	164.0	115.7	50.7	15.1	3.0	0	0	1397.0
0.50	0	2.3	52.2	222.3	362.9	233.6	117.9	78.6	52.9	15.9	3.0	1.5	0	1143.0
0.60	0	0	14.4	187.5	322.0	276.7	117.2	41.6	24.2	15.9	1.5	1.5	1.5	1003.9
0.70	0	0	7.6	119.4	306.9	303.1	125.5	30.2	18.1	12.1	0	0	0	923.0
0.80	0	0	4.5	59.0	225.3	276.7	109.6	31.0	13.6	4.5	0.8	0	0	725.0
0.90	0	0	0	21.9	156.5	251.0	130.8	47.6	10.6	2.3	2.3	0	0	622.9
1.00	0	0	0	9.8	104.3	186.0	155.7	54.4	18.9	2.3	2.3	0	0	533.7
1.10	0	0	0	0.8	65.0	164.0	148.9	73.3	25.7	8.3	2.3	0	0	488.4
1.20	0	0	0	0	26.5	104.3	130.0	68.0	37.0	6.0	6.0	0	0	378.0
1.30	0	0	0	0	3.8	48.4	93.7	68.8	28.7	7.6	0.8	0	0	251.7
1.40	0	0	0	0	5.3	46.9	77.1	69.5	31.8	0.8	0.8	0	0	232.1
1.50	0	0	0	0	0	22.7	66.5	77.1	40.8	3.8	1.5	0	0	212.4
1.60	0	0	0	0	0	9.1	60.5	69.5	40.8	18.1	0	0	0	198.1
1.70	0	0	0	0	0	1.5	37.0	41.6	40.8	20.4	0.8	0	0	142.1
1.80	0	0	0	0	0	1.5	21.9	24.9	24.9	15.1	2.3	0	0	90.7
1.90	0	0	0	0	0	0.8	7.6	22.7	20.4	17.4	2.3	0	0	71.1
2.00	0	0	0	0	0	0	2.3	8.3	11.3	7.6	4.5	0	0	34.0
Hs / ωp	2.09	1.80	1.57	1.40	1.26	1.14	1.05	0.97	0.90	0.84	0.79	0.74	0.70	TOTAL
SUM	0.0	15.1	244.2	1125.6	2441.0	2665.6	1761.4	1023.6	508.8	176.1	34.0	3.0	1.5	10000.0



3. Excitation

Navigation limits. Weather Conditions.

- All developed database contain results for 15 types of navigation limit, each one represented by a significant wave height Hs within the range IN(0.6 < x ≤ 2) as defined in **BV NR217 rules.**

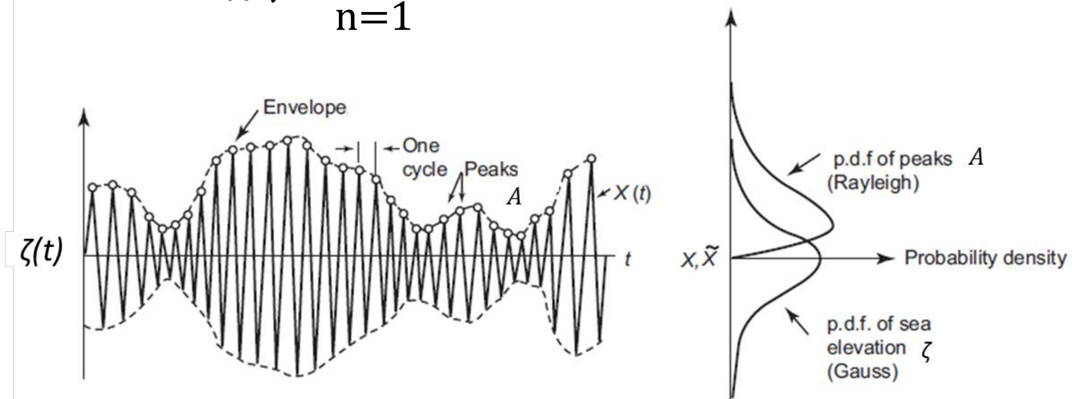
Physical Notation	BV NR17 Notation
Hs = 0.6 m	IN(0.6)
Hs = 0.7 m	IN(0.7)
Hs = 0.8 m	IN(0.8)
Hs = 0.9 m	IN(0.9)
Hs = 1.0 m	IN(1.0)
Hs = 1.1 m	IN(1.1)
Hs = 1.2 m	IN(1.2)
Hs = 1.3 m	IN(1.3)
Hs = 1.4 m	IN(1.4)
Hs = 1.5 m	IN(1.5)
Hs = 1.6 m	IN(1.6)
Hs = 1.7 m	IN(1.7)
Hs = 1.8 m	IN(1.8)
Hs = 1.9 m	IN(1.9)
Hs = 2.0 m	IN(2.0)

3. Excitation

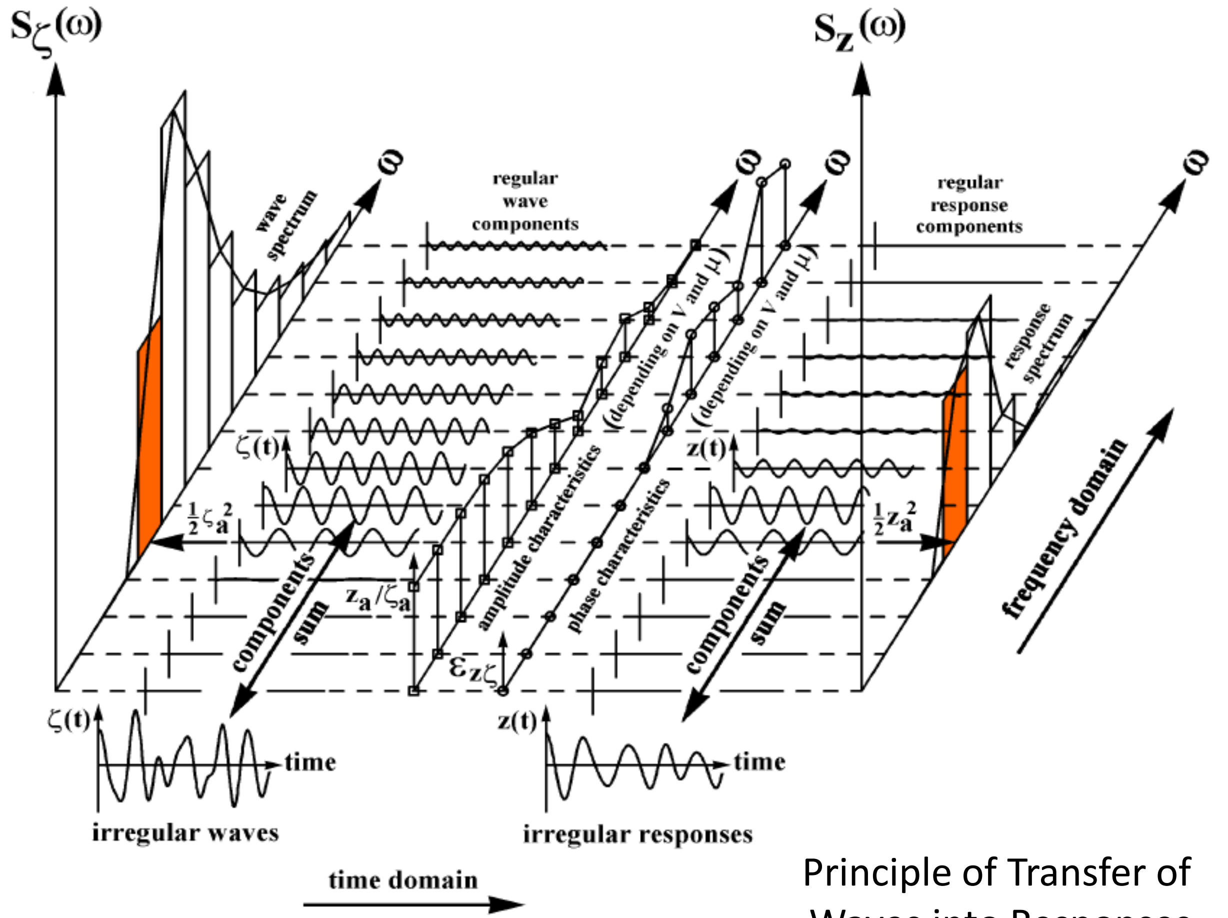
Statistical Distribution of waves

$$S_\zeta(\omega_n)\cdot\Delta\omega = \sum_{\omega_n}^{\omega_n+\Delta\omega} \frac{1}{2}\zeta_{a_n}{}^2(\omega)$$

$$\zeta(x,t) = \lim_{N\to\infty} \sum_{n=1}^{N} \zeta_{a_n}\cos(-k_n x - \omega_n t + \theta_n)$$



Rayleigh Distribution



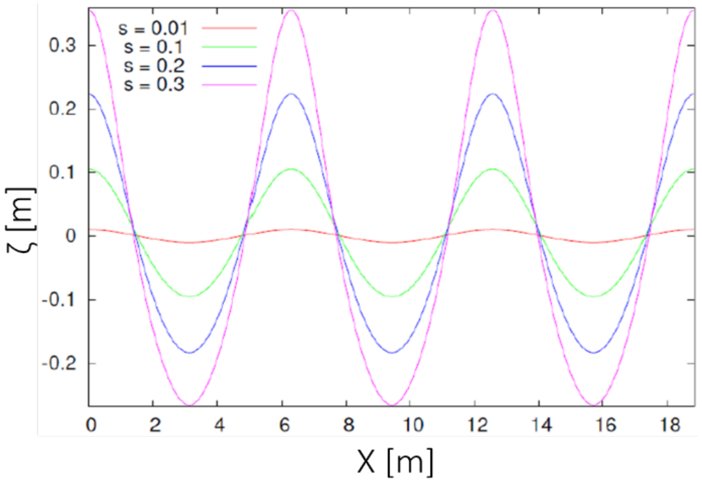
Principle of Transfer of Waves into Responses

3. Excitation

Belgian Coastal **Scatter Diagram**: Wave Steepness.

$$\varepsilon = \frac{\pi H}{\lambda} = \frac{2\pi A}{\lambda}$$

- If $\varepsilon > 0.01$, nonlinear effects are present, as in the range of navigation IN[$0.6 < x < 2.0$].



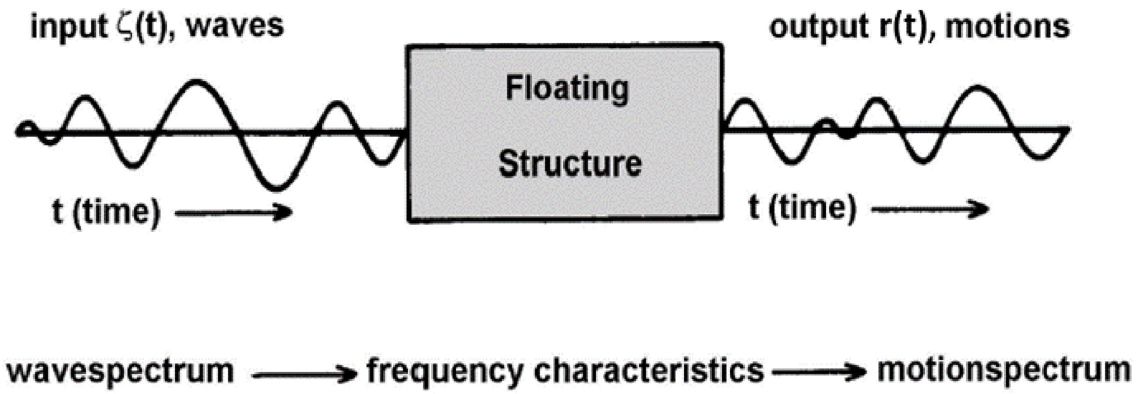
Hs / Tp	3.00	3.50	4.00	4.50	5.00	5.50	6.00	6.50	7.00	7.50	8.00	8.50	9.00
0.20			0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.01			
0.30		0.05	0.04	0.03	0.02	0.02	0.02	0.01	0.01	0.01			
0.40		0.07	0.05	0.04	0.03	0.03	0.02	0.02	0.02	0.01	0.01		
0.50		0.08	0.06	0.05	0.04	0.03	0.03	0.02	0.02	0.02	0.02	0.01	
0.60			0.08	0.06	0.05	0.04	0.03	0.03	0.02	0.02	0.02	0.02	0.01
0.70			0.09	0.07	0.06	0.05	0.04	0.03	0.03	0.03			
0.80			0.10	0.08	0.06	0.05	0.04	0.04	0.03	0.03	0.03		
0.90				0.09	0.07	0.06	0.05	0.04	0.04	0.03	0.03		
1.00				0.10	0.08	0.07	0.06	0.05	0.04	0.04	0.03		
1.10				0.11	0.09	0.07	0.06	0.05	0.05	0.04	0.03		
1.20					0.10	0.08	0.07	0.06	0.05	0.04	0.04		
1.30					0.10	0.09	0.07	0.06	0.05	0.05	0.04		
1.40					0.11	0.09	0.08	0.07	0.06	0.05	0.04		
1.50						0.10	0.08	0.07	0.06	0.05	0.05		
1.60						0.11	0.09	0.08	0.07	0.06			
1.70						0.11	0.10	0.08	0.07	0.06	0.05		
1.80						0.12	0.10	0.09	0.07	0.06	0.06		
1.90							0.11	0.09	0.08	0.07	0.06		
2.00							0.11	0.10	0.08	0.07	0.06		
Hs / ω_p	2.09	1.80	1.57	1.40	1.26	1.14	1.05	0.97	0.90	0.84	0.79	0.74	0.70

Direction of incrementing value

4. Linear Response

Linear Potential Theory: Linear Mass-Spring System

Block Diagram for a Linear System. Linear relation between Motions and Waves:

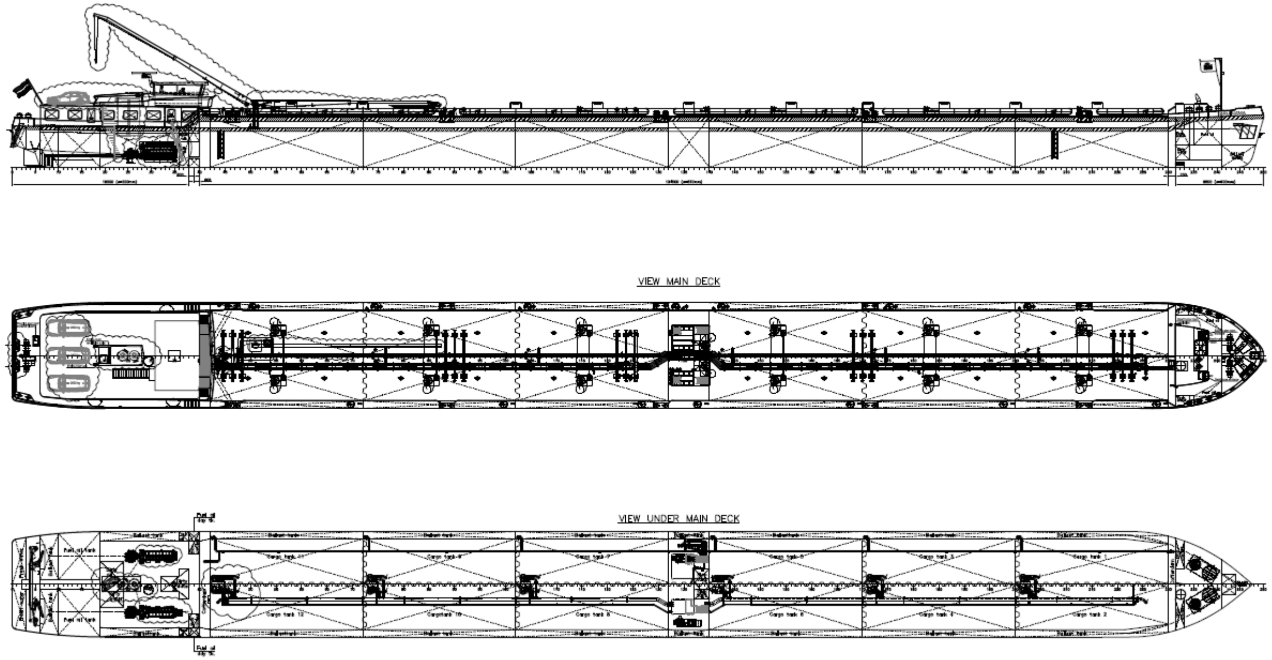


4. Linear Response

Investigated vessel within the study

- Inland-Navigation ship-database composed of:
  - ➢ 40 Tankers;
  - ➢ 4 containerships;
  - ➢ 1 cargo vessel;
  - ➢ 1 bulkcarrier.

- All of them complying with the BV Rules NR 217;
- Length ∈ [33 – 135] m;
- Breadth ∈ [5 – 23] m;
- Draught ∈ [2.2 – 5.2] m;
- Displacement ∈ [400 – 14700] ton;
- For the loading conditions studied, Block Coefficient (C_B) $\geq$ 0.82 in all the cases, even for containerships. 14 ships even have a $C_B \geq 0.90$.

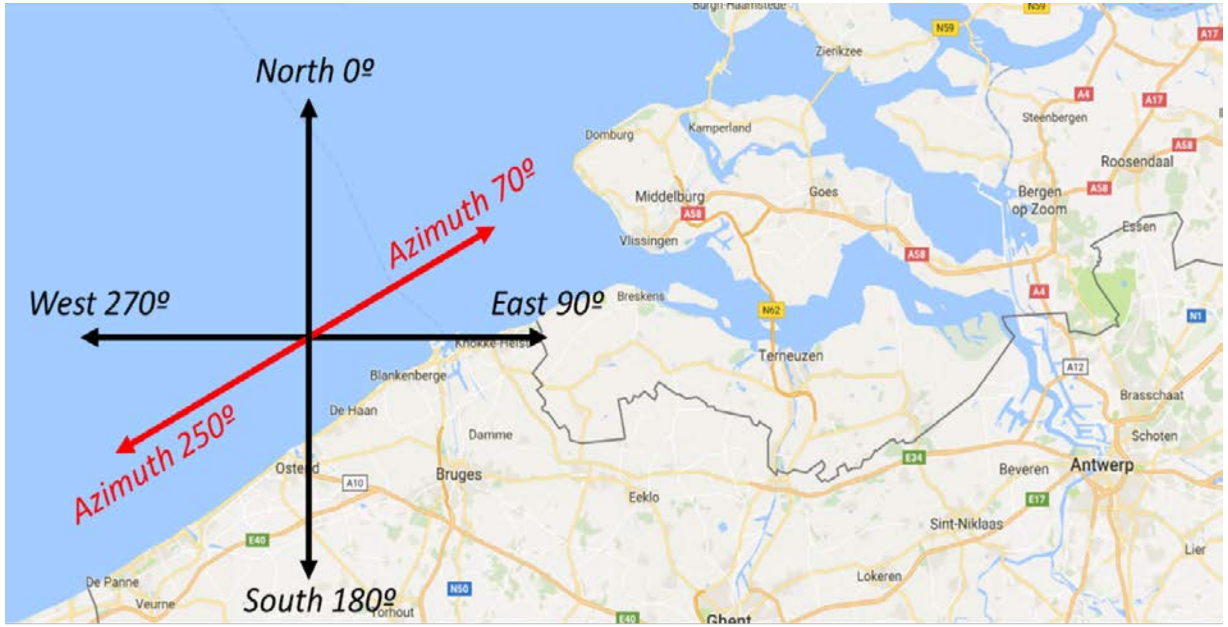


General Arrangement of a typical IN tanker

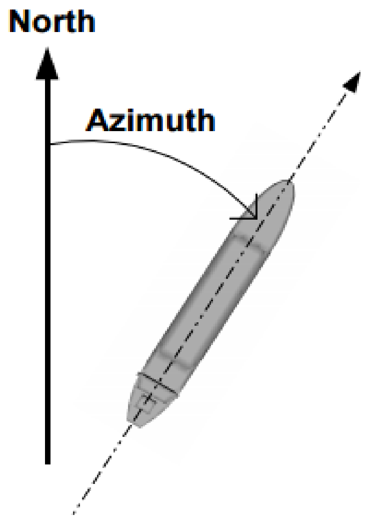
4. Linear Response

Return Period

- 20 years of life;
- Return Period: 85% (17 years) is assumed to be spent in operation;
- Sailing within the range of navigation IN[0.6 < x < 2.0];
- Operation: 50% of the time sailing in Azimuth 70º and 50% in Azimuth 250º.



Belgium coastal area. Each vessel's azimuth is specified.



Azimuth Reference = α'

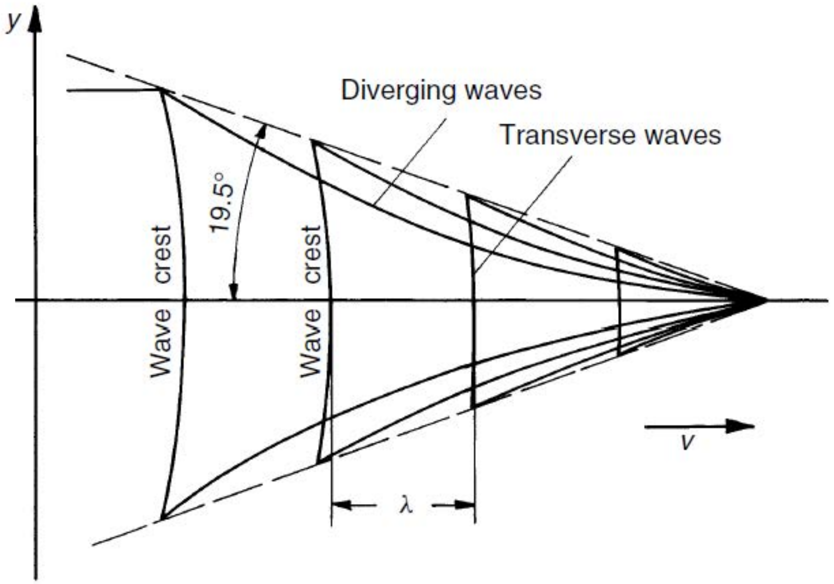
4. Linear Response

Forward Speed seakeeping effects

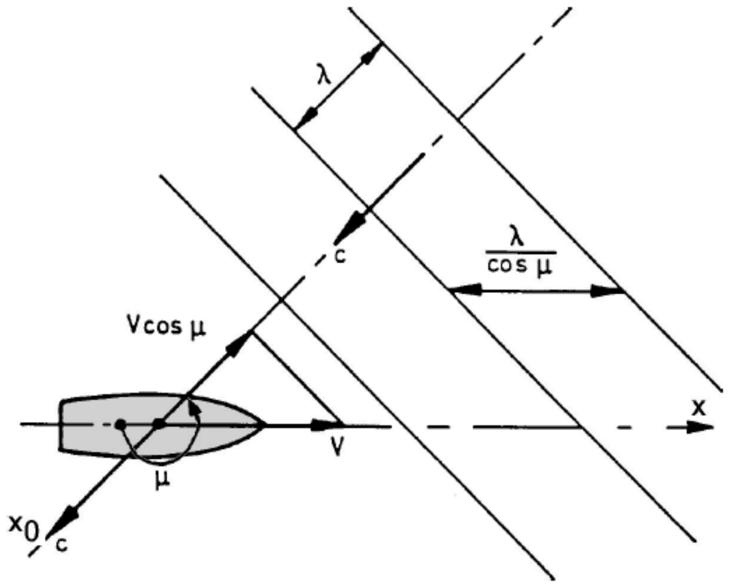
Represented as following:

1) Modifications of the free surface conditions, due to perturbations generated by the advance of the ship;
2) Wave encounter frequency, ω_e.

1:



2:

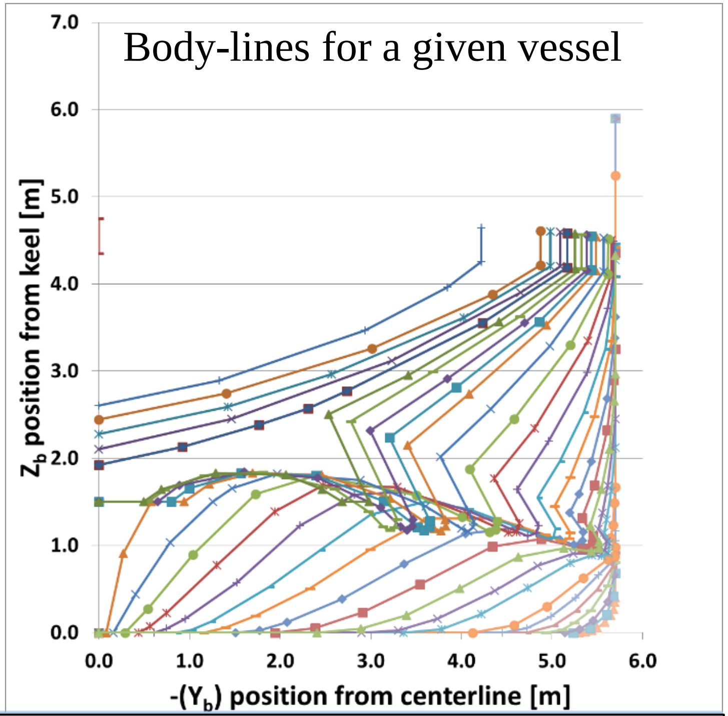


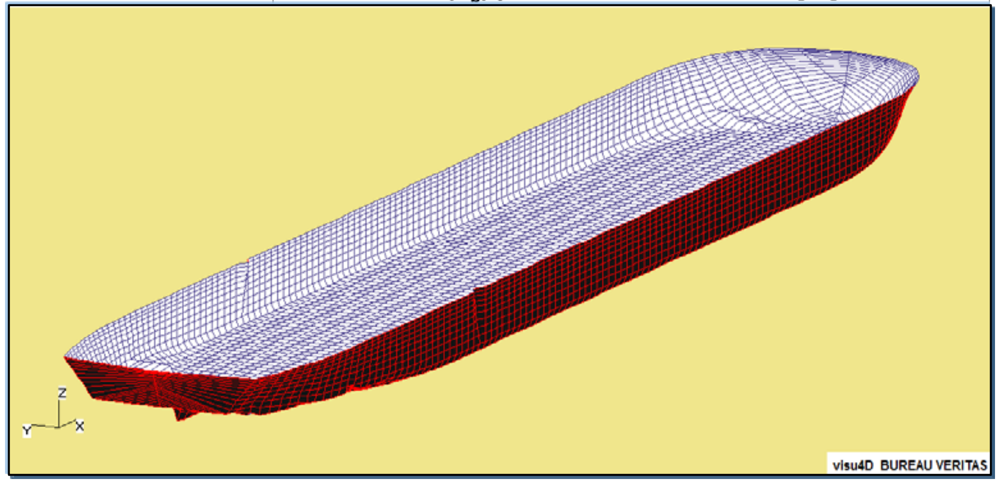
To model the forward speed at 10 knots, it was used only the correction of the encounter frequency.

5. Direct Calculations in HYDROSTAR

hsmsh modulus: Mesh Generation

- **hsmsh input**
  - ➢Body-lines (from Bureau Veritas documents);
  - ➢Draught of the ship for fully loaded conditions.
  - ➢Trim and Heel angle of the ship, imposed at 0 degrees.
- **hsmsh output**
  - ➢ Mesh generation according 3D linear Panel Method.
  - ➢ **Boundary Condition on the oscillating hull surface**



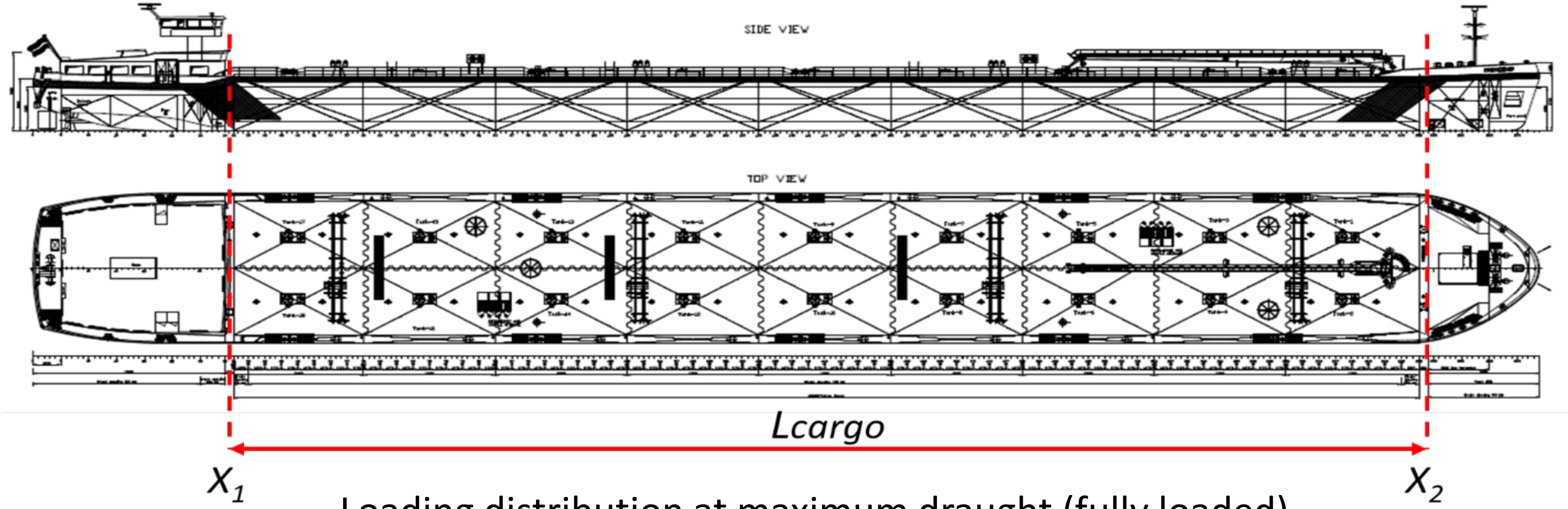


LOA = 135 m; B = 22.5 m. Nlong = 110 divisions; Ntrans = 15 divisions.

5. Direct Calculations in HYDROSTAR

hstat modulus: Hydrostatic computation in still water conditions

- **hstat input**
  - Longitudinal mass distribution of fully loading conditions (from hydrostatic documents);
  - Corrected centre of gravity position due to free-surface effects within tanks (from hydrostatic documents);
  - Gyration radius on the x-axis, to account transversal mass distribution, defined as: $\mathrm{K_{xx}} = 0.35 \cdot \mathrm{B}$.



Loading distribution at maximum draught (fully loaded).

5. Direct Calculations in HYDROSTAR

hstat modulus: Hydrostatic computation in still water conditions

- **hstat output**
  - Hydrostatic characteristics are calculated: (LCB, 0, VCB);
  - Inertia matrix [m] is obtained for zero-trim conditions: G(x, y) = (LCB, 0);
  - Hydrostatic restoring coefficients in stiffness matrix [K];

$$\mathrm{m} = \begin{pmatrix} \rho\nabla & 0 & 0 & 0 & 0 & 0 \\ 0 & \rho\nabla & 0 & 0 & 0 & 0 \\ 0 & 0 & \rho\nabla & 0 & 0 & 0 \\ 0 & 0 & 0 & I_{xx} & 0 & 0 \\ 0 & 0 & 0 & 0 & I_{yy} & 0 \\ 0 & 0 & 0 & 0 & 0 & I_{zz} \end{pmatrix}$$

Mass matrix.

$$\mathrm{K} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & K_{33} & 0 & K_{35} & 0 \\ 0 & 0 & 0 & K_{44} & 0 & 0 \\ 0 & 0 & K_{53} & 0 & K_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

Hydrostatic restoring matrix.

5. Direct Calculations in HYDROSTAR

hsrdf modulus: Diffraction-radiation computation in wave conditions

- **hsrdf input**
  - ➢Wave frequencies: from 0.2 to 2.2 [rad/s];
  - ➢Wave headings: from 0 to 350 degrees, for an increasing step of 10 degree;
  - ➢Water depth (sea bed) assumed to be constant at 15 m;
  - ➢Ship forward speed imposed at 10 knots. ω_e approximation is considered in the corresponding Green function.

- **hsrdf output**
  - ➢Linear radiation damping matrix;
  - ➢Added-mass matrix;
  - ➢Wave excitation loads.

$$a = \begin{pmatrix} a_{11} & 0 & a_{13} & 0 & a_{15} & 0 \\ 0 & a_{22} & 0 & a_{24} & 0 & a_{26} \\ a_{31} & 0 & a_{33} & 0 & a_{35} & 0 \\ 0 & a_{42} & 0 & a_{44} & 0 & a_{46} \\ a_{51} & 0 & a_{53} & 0 & a_{55} & 0 \\ 0 & a_{62} & 0 & a_{64} & 0 & a_{66} \end{pmatrix}$$

Added-mass matrix

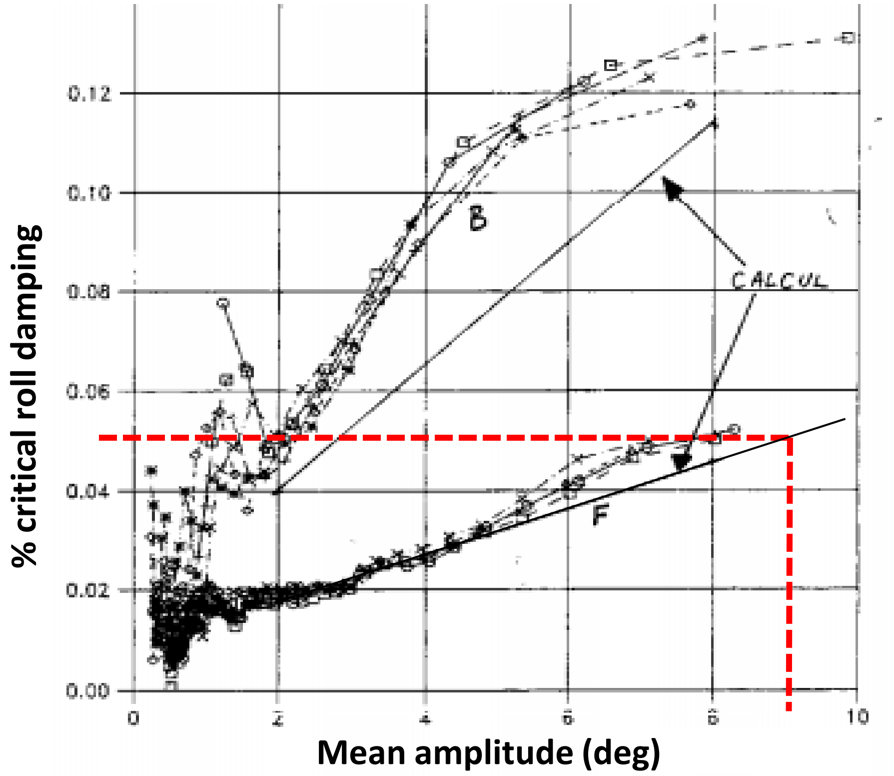
$$b = \begin{pmatrix} b_{11} & 0 & b_{13} & 0 & b_{15} & 0 \\ 0 & b_{22} & 0 & b_{24} & 0 & b_{26} \\ b_{31} & 0 & b_{33} & 0 & b_{35} & 0 \\ 0 & b_{42} & 0 & b_{44} & 0 & b_{46} \\ b_{51} & 0 & b_{53} & 0 & b_{55} & 0 \\ 0 & b_{62} & 0 & b_{64} & 0 & b_{66} \end{pmatrix}$$

Linear radiation damping matrix

5. Direct Calculations in HYDROSTAR

hsmcn modulus: Motion computation

- **Roll modes of motion**, correction made according to **J. M. Orozco et al. (2002)** for full loaded case.
- Roll damping coefficient: 5% of the critical roll damping:



Roll damping coefficient (in % of the critical damping) obtained by the decay tests and Ikeda-H. method.

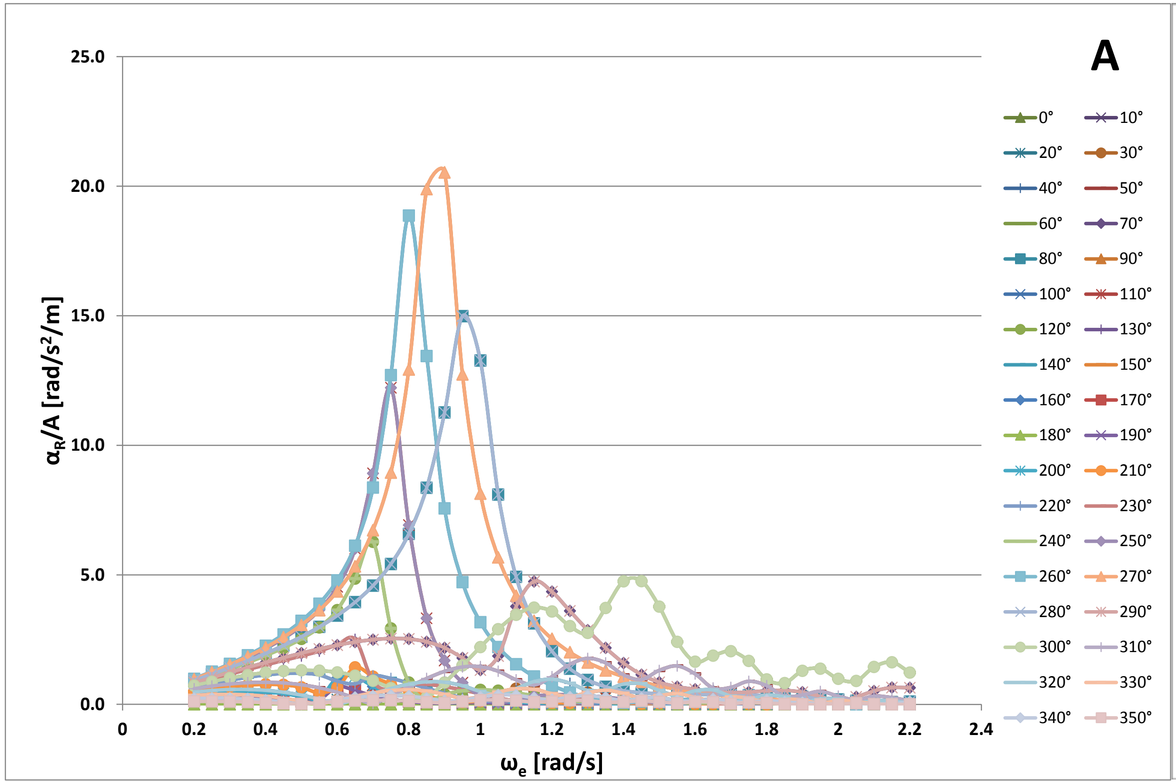
- **hsmcn output**
  - Motions, velocities and accelerations.

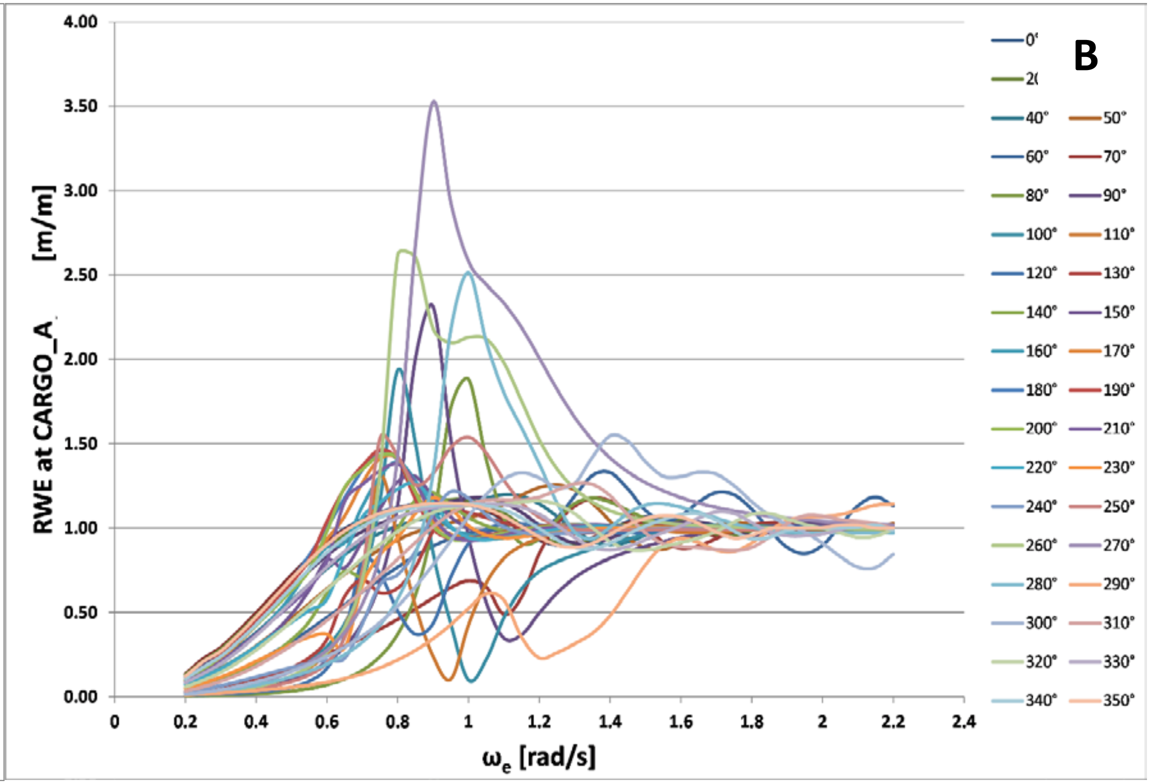
5. Direct Calculations in HYDROSTAR

hsrao modulus: Construction of the transfer functions

- RAO of Motions, velocities and accelerations on and around G(x, y, z);
- RAO of relative elevation at imposed points around ship hull;
- RAO of loads at a defined point around the ship hull.

A: Roll-acceleration transfer function for a given vessel.
B: RWE transfer function for a given vessel.





5. Direct Calculations in HYDROSTAR

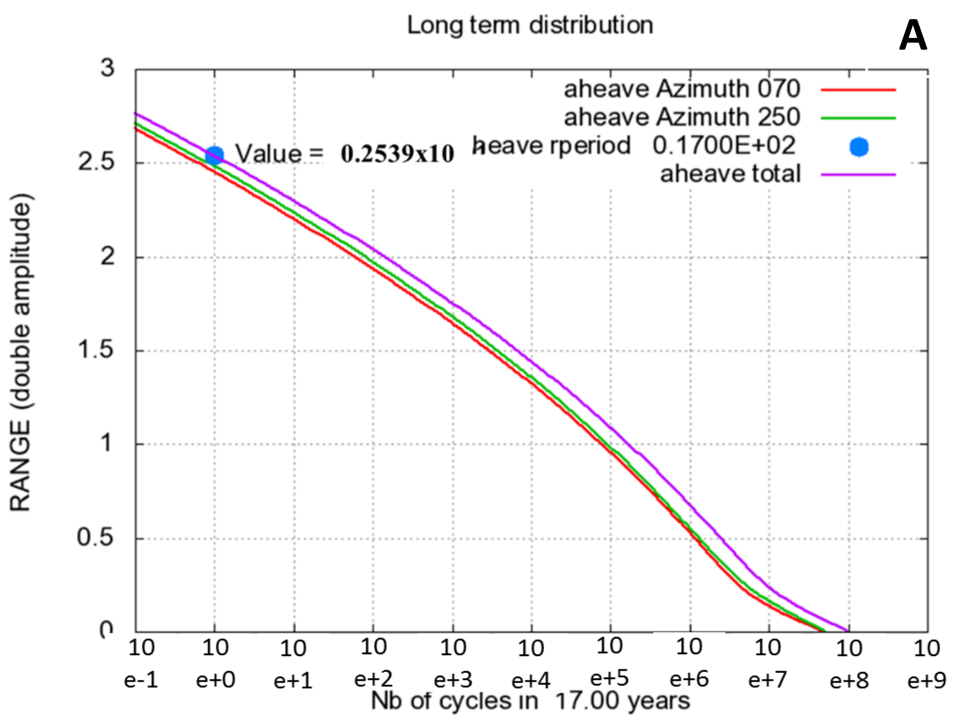
hspec modulus: Long term value for a given response

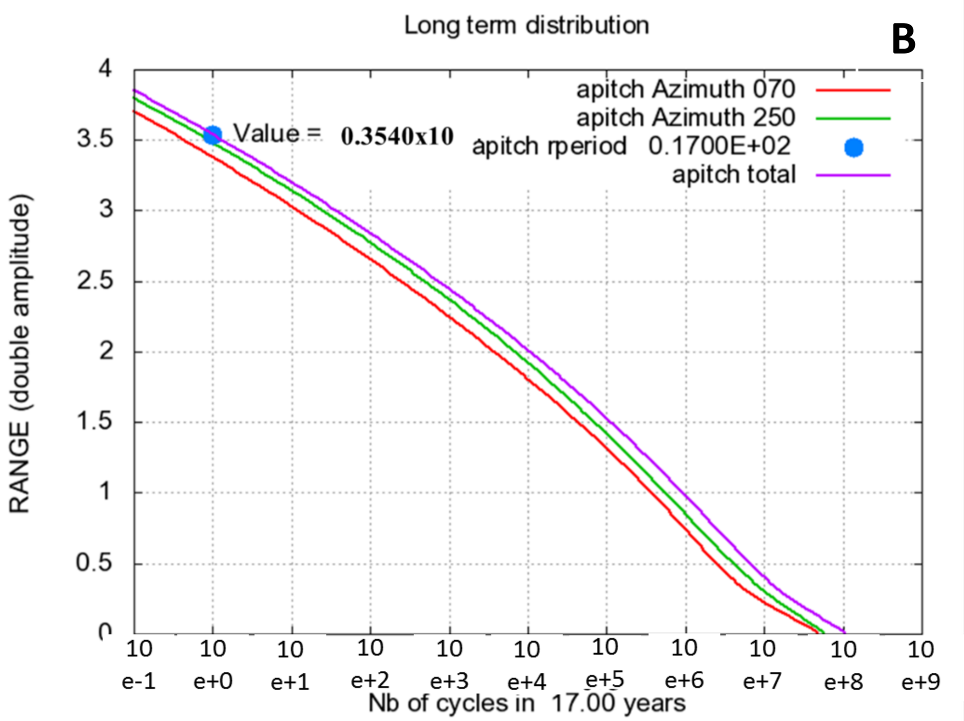
- **hsprs output**

➢ Long term values (in term of double amplitude).

➢ Data-base is created for 46 ships.

A: Heave acceleration long-term-value for a given vessel.
B: Pitch acceleration long-term-value for a given vessel.





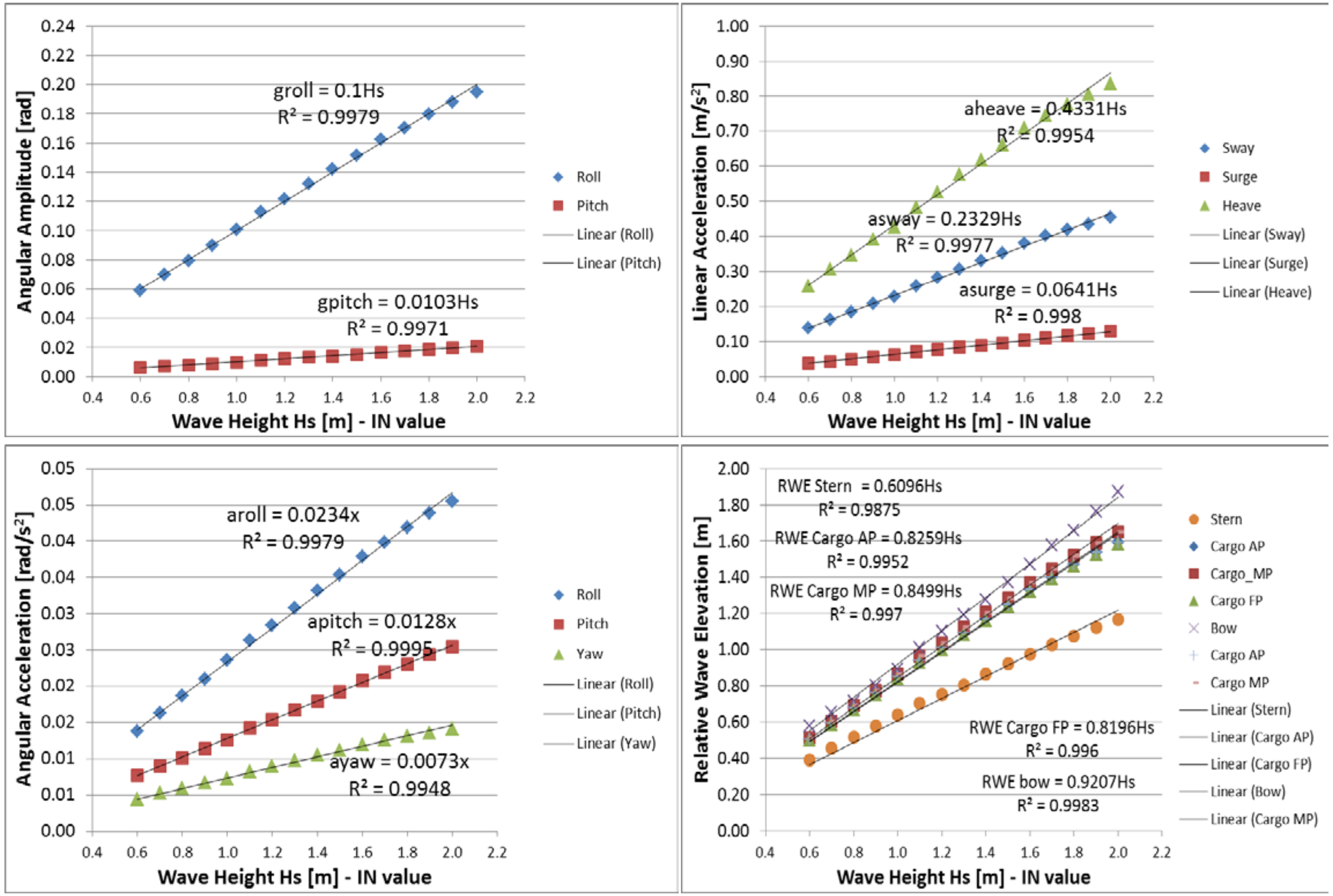
6. Empirical Formulas

NR217 rules. General Scheme

Common pattern in all of the motion and acceleration **BV NR217** formulas can be observed:

$$\text{Entity}_X = a_{B(X,Hs)} \cdot Y_X$$

- Entity_X = any entity for a given vessel X.
- Y = rest of the formula for a vessel X.
- $a_{B(X,Hs)}$ = motion and acceleration parameter for a vessel X and a limit of navigation Hs.



Long-term values. Motion; accelerations; Relative Wave Elevation vs Hs

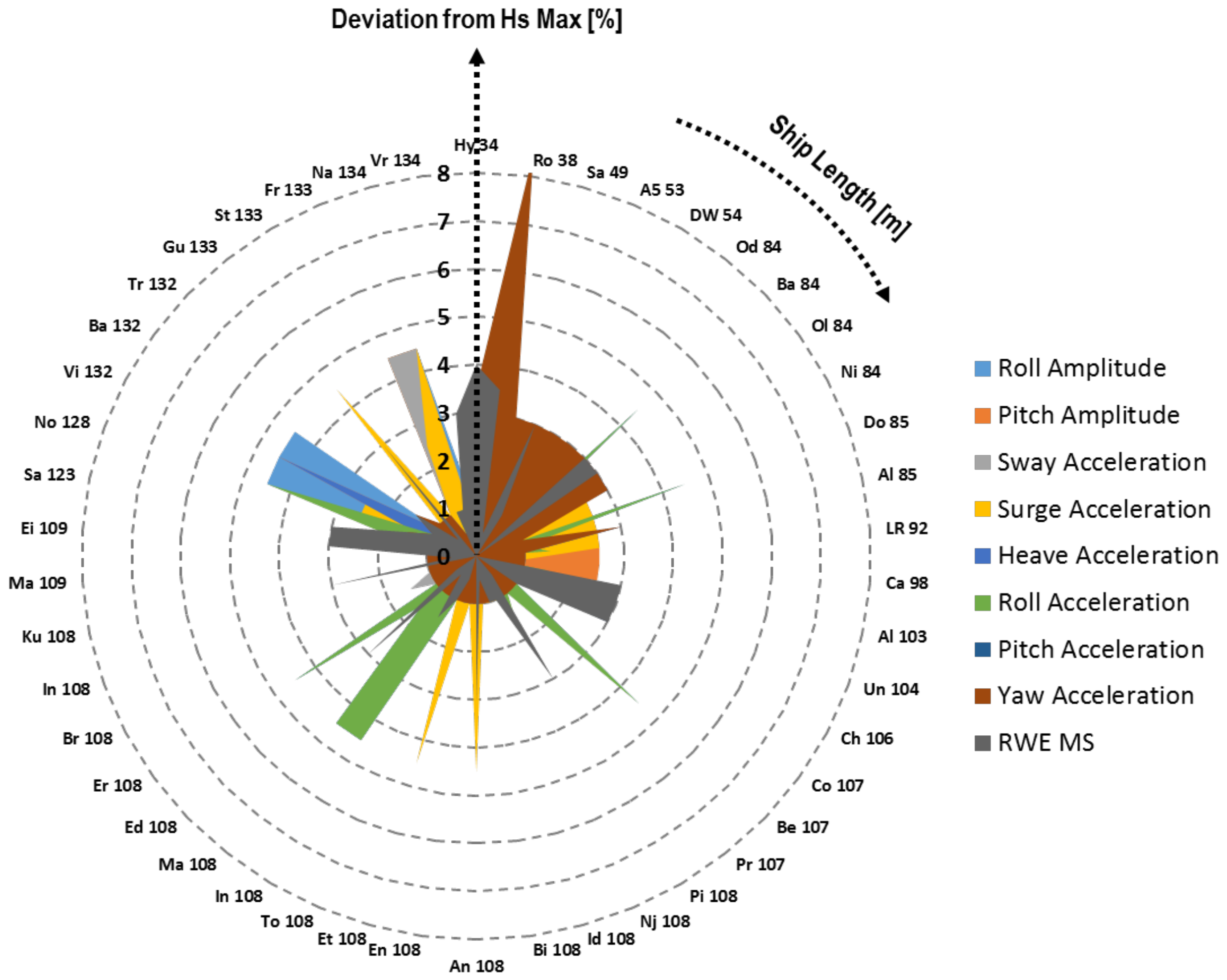
6. Empirical Formulas

NR217 rules. General Scheme

Common pattern in all of the motion and acceleration **BV NR217** formulas can be observed:

$$\text{Entity}_X = a_{B(X,Hs)} \cdot Y_X$$

- Entity_X = any entity for a given vessel X.
- Y = rest of the formula for a vessel X.
- $a_{B(X,Hs)}$ = motion and acceleration parameter for a vessel X and a limit of navigation Hs.



Deviation from limit of navigation Hs = 2.0 m

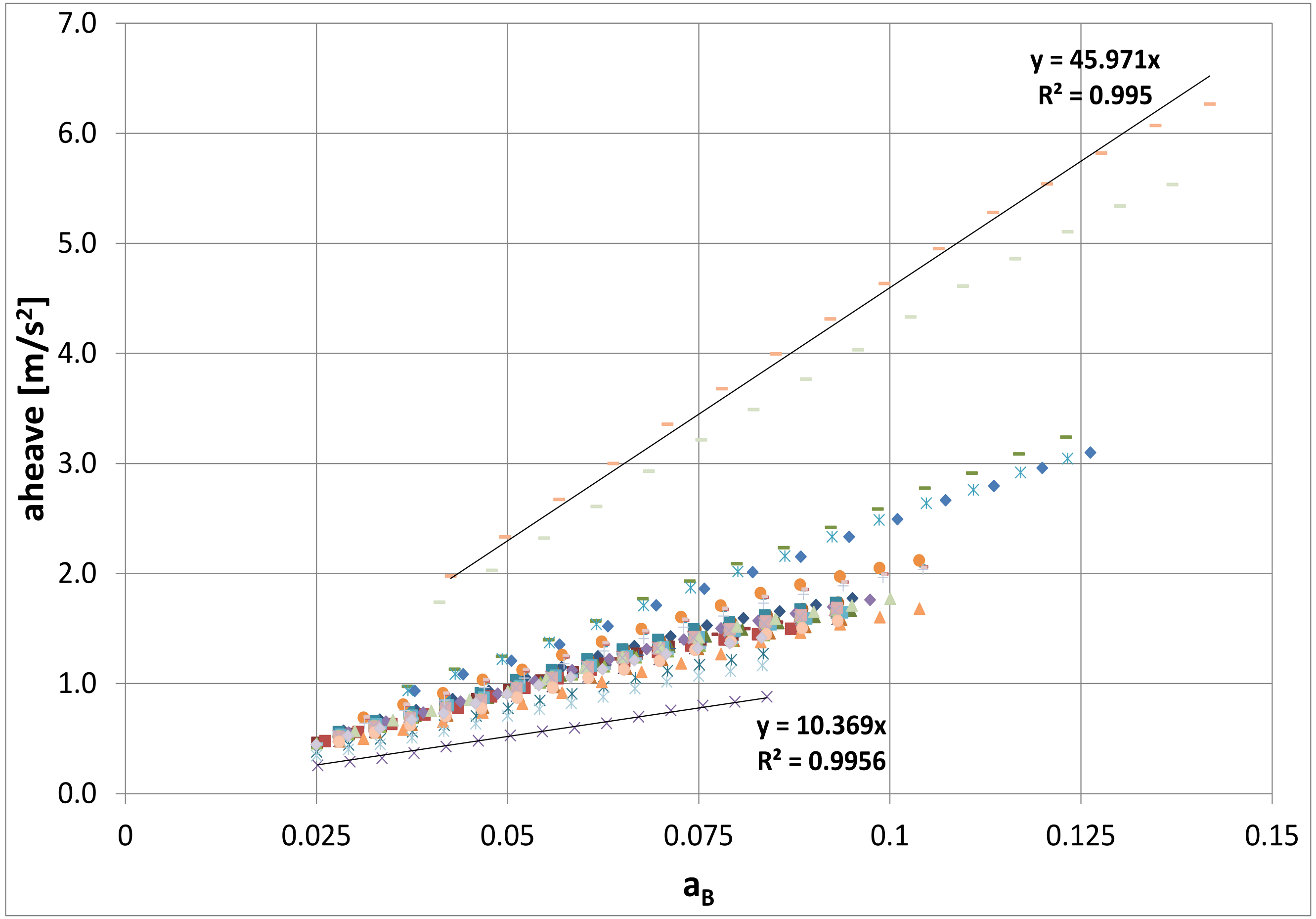
6. Empirical Formulas

Proposed Methodology

Common pattern in all of the motion and acceleration **BV NR217** formulas can be observed:

$$\text{Entity}_X = a_{B(X,Hs)} \cdot Y_X \quad \longrightarrow \quad Y_X = \frac{\text{Entity}_X}{a_{B(X,Hs)}}$$

- Entity_X = any entity for a given vessel X.
- Y = rest of the formula for a vessel X.
- $a_{B(X,Hs)}$ = motion and acceleration parameter for a vessel X and a limit of navigation Hs.



Heave acceleration vs a_B. Range of slope values is assesed.

6. Empirical Formulas

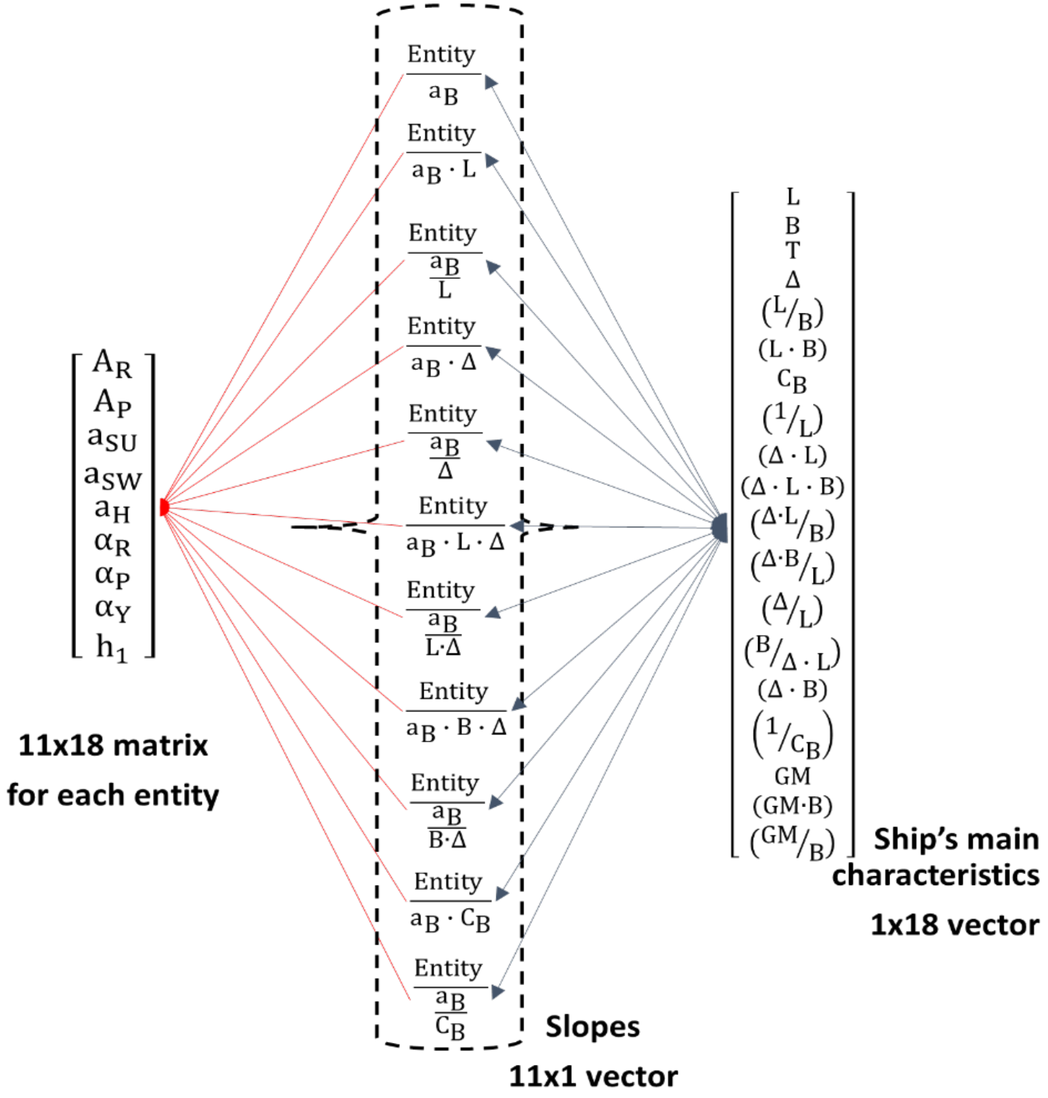
Proposed Methodology

Calculating several kind of slopes.

It is desired that the proposed empirical formulas are built in terms of the ship's main characteristics:

- Length between perpendiculars (L);
- Moulded beam (B);
- Maximum draught (T);
- Displacement for maximum load condition (Δ);
- Shape characteristics:
    - o Ship slenderness (L/B);
    - o Block coefficient (C_B) are taken into account.

Some combinations of main characteristic variables are as well considered



Heave acceleration vs a_B. Range of slope values is assesed.

6. Empirical Formulas

Final Proposal for linear effects

E.g. Sway Acceleration, in [m/s²]

- If $\Delta < 1700$ ton :

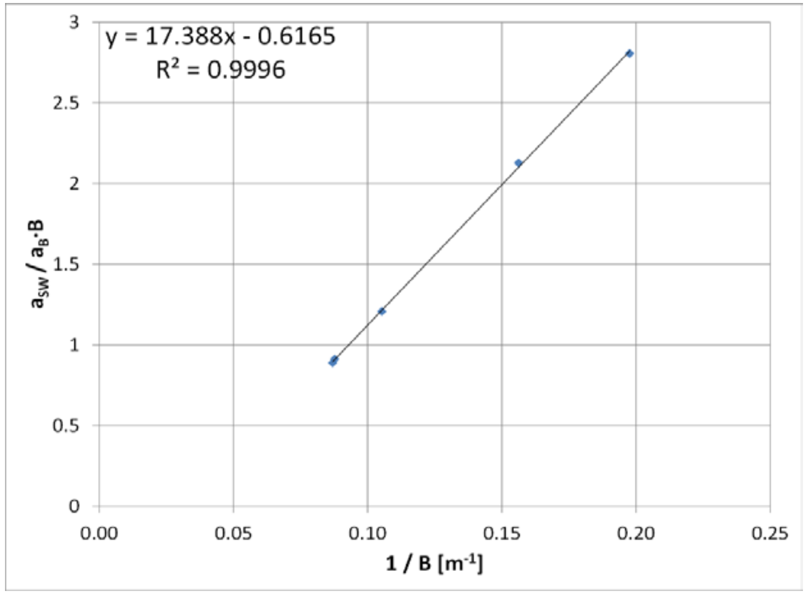
  $$a_{SW} = a_B \cdot (17.388 - 0.6165B)$$

- If $(1700 < \Delta < 5000)$ ton :

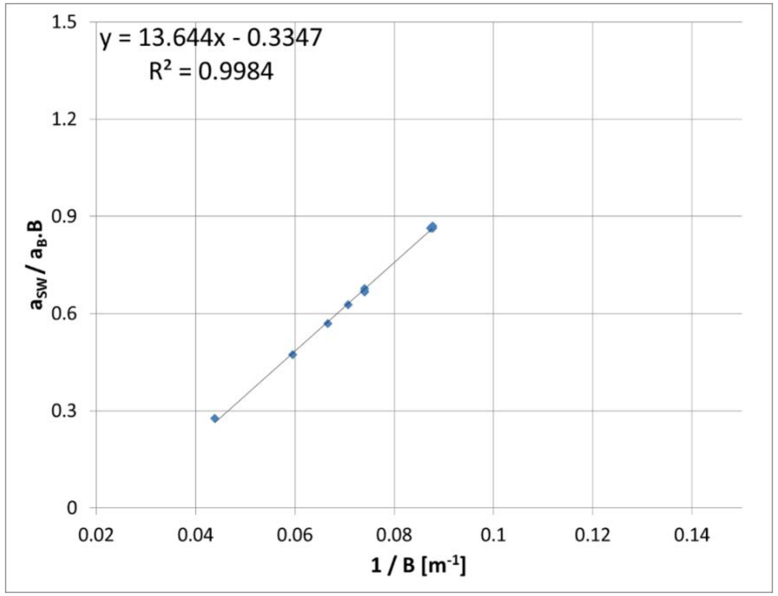
  $$a_{SW} = a_B \cdot (15.074 - 0.4297B)$$

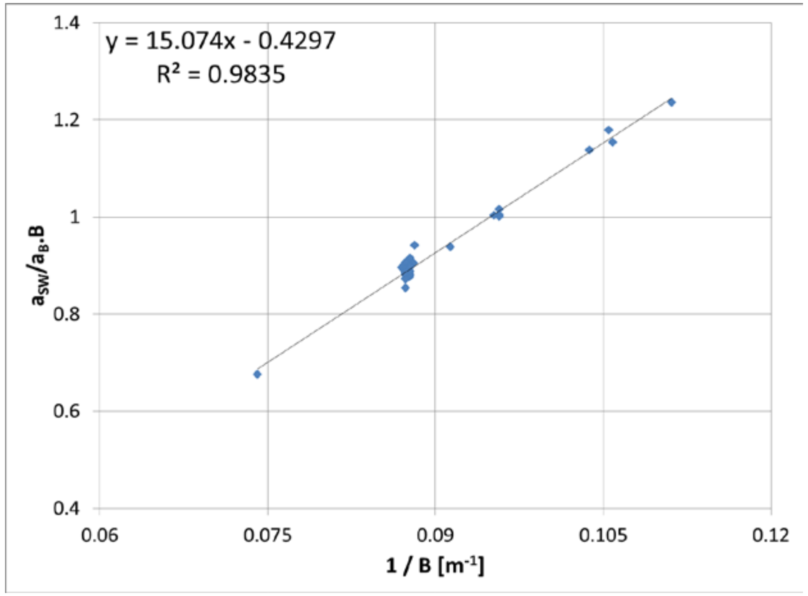
- If $(\Delta > 5000)$ ton :

  $$a_{SW} = a_B \cdot (13.644 - 0.3347B)$$



Regression Process for Sway Acceleration Entity. Tendencies found.





6. Empirical Formulas

Final Proposal for linear effects

E.g. Sway Acceleration, in [m/s²]

- If $\Delta < 1700$ ton :

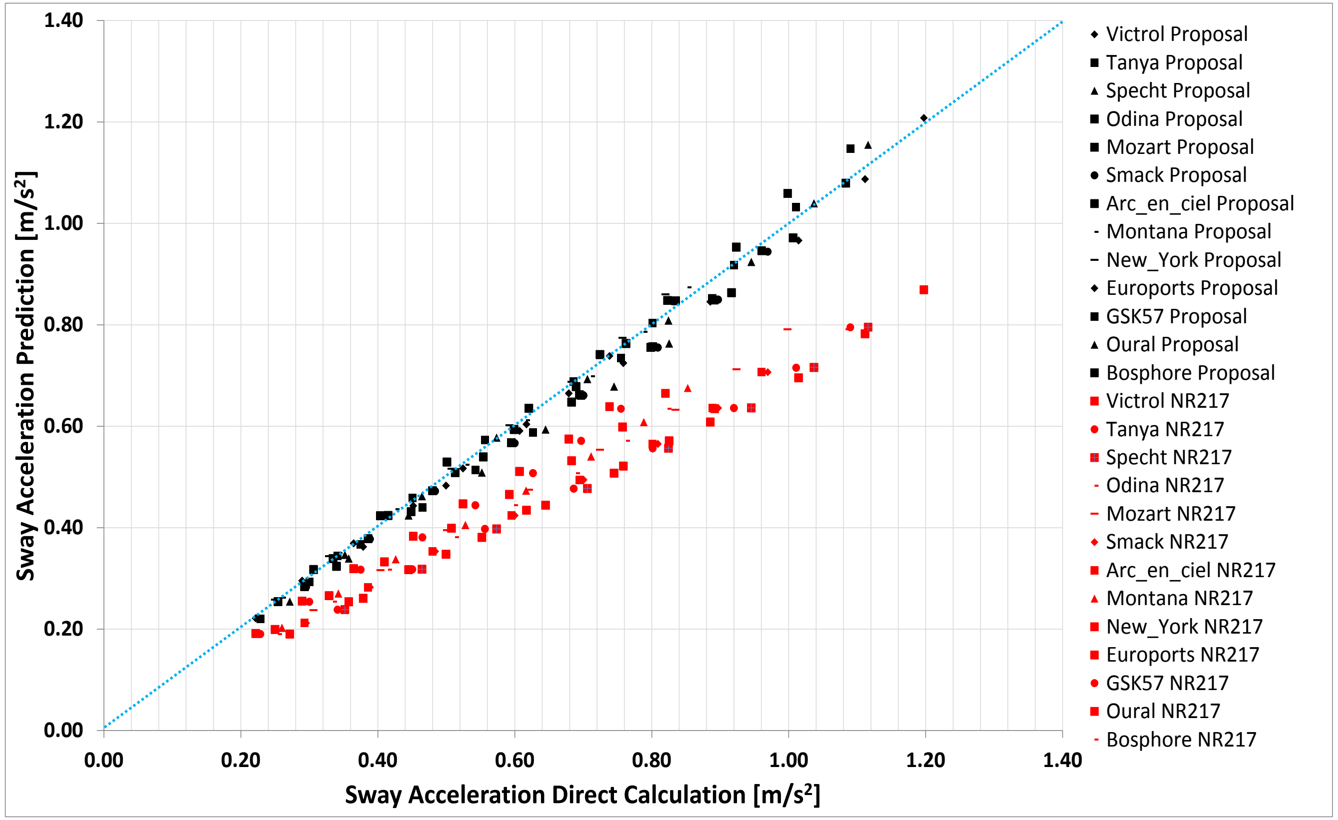
$$a_{SW} = a_B \cdot (17.388 - 0.6165B)$$

- If $(1700 < \Delta < 5000)$ ton :

$$a_{SW} = a_B \cdot (15.074 - 0.4297B)$$

- If $(\Delta > 5000)$ ton :

$$a_{SW} = a_B \cdot (13.644 - 0.3347B)$$



Validation process using Rudacovic (2015) vessels. BV NR217 vs final proposal.

6. Empirical Formulas

Final Proposal for linear effects

E.g. Sway Acceleration, in [m/s²]

- If $\Delta < 1700$ ton :

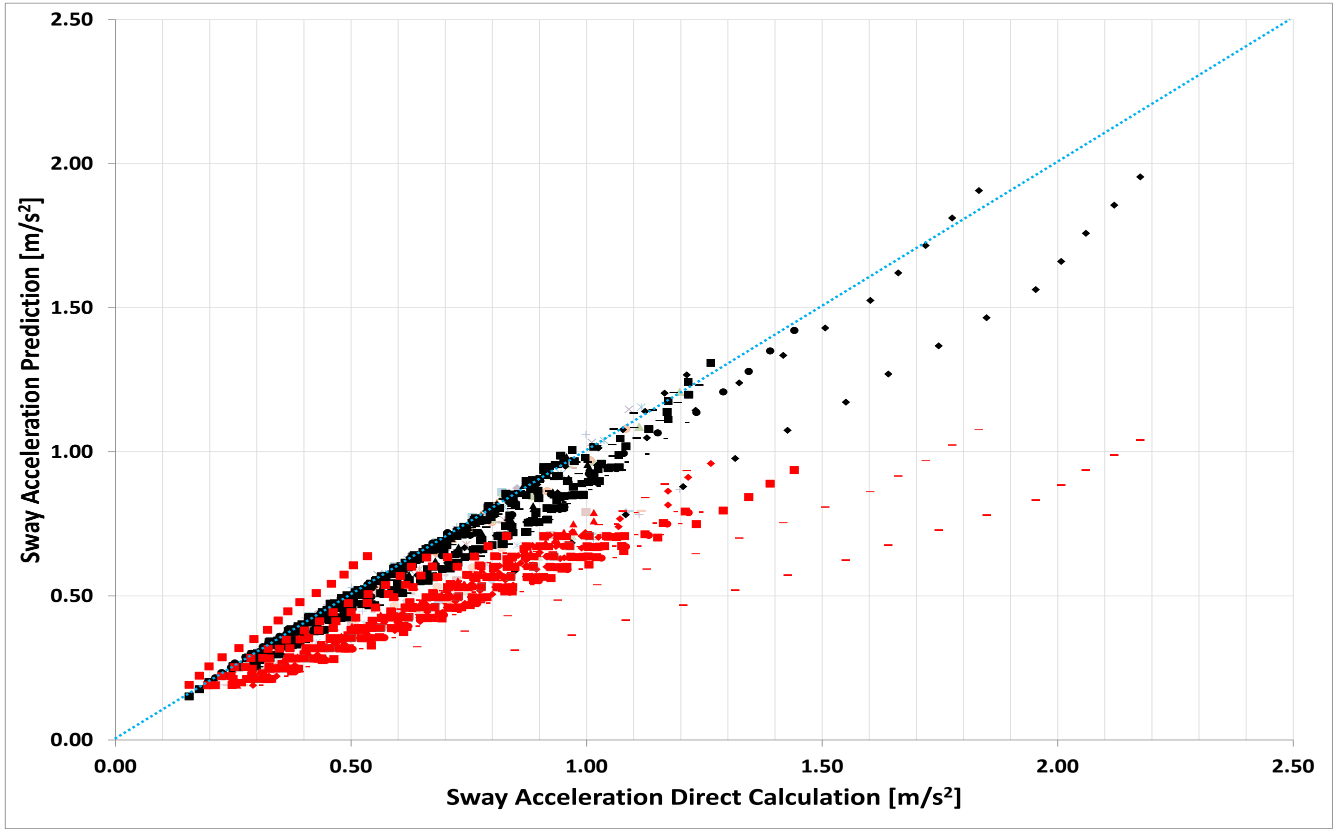
$$a_{SW} = a_B \cdot (17.388 - 0.6165B)$$

- If $(1700 < \Delta < 5000)$ ton :

$$a_{SW} = a_B \cdot (15.074 - 0.4297B)$$

- If $(\Delta > 5000)$ ton :

$$a_{SW} = a_B \cdot (13.644 - 0.3347B)$$



Validation process using all data available. BV NR217 vs final proposal.

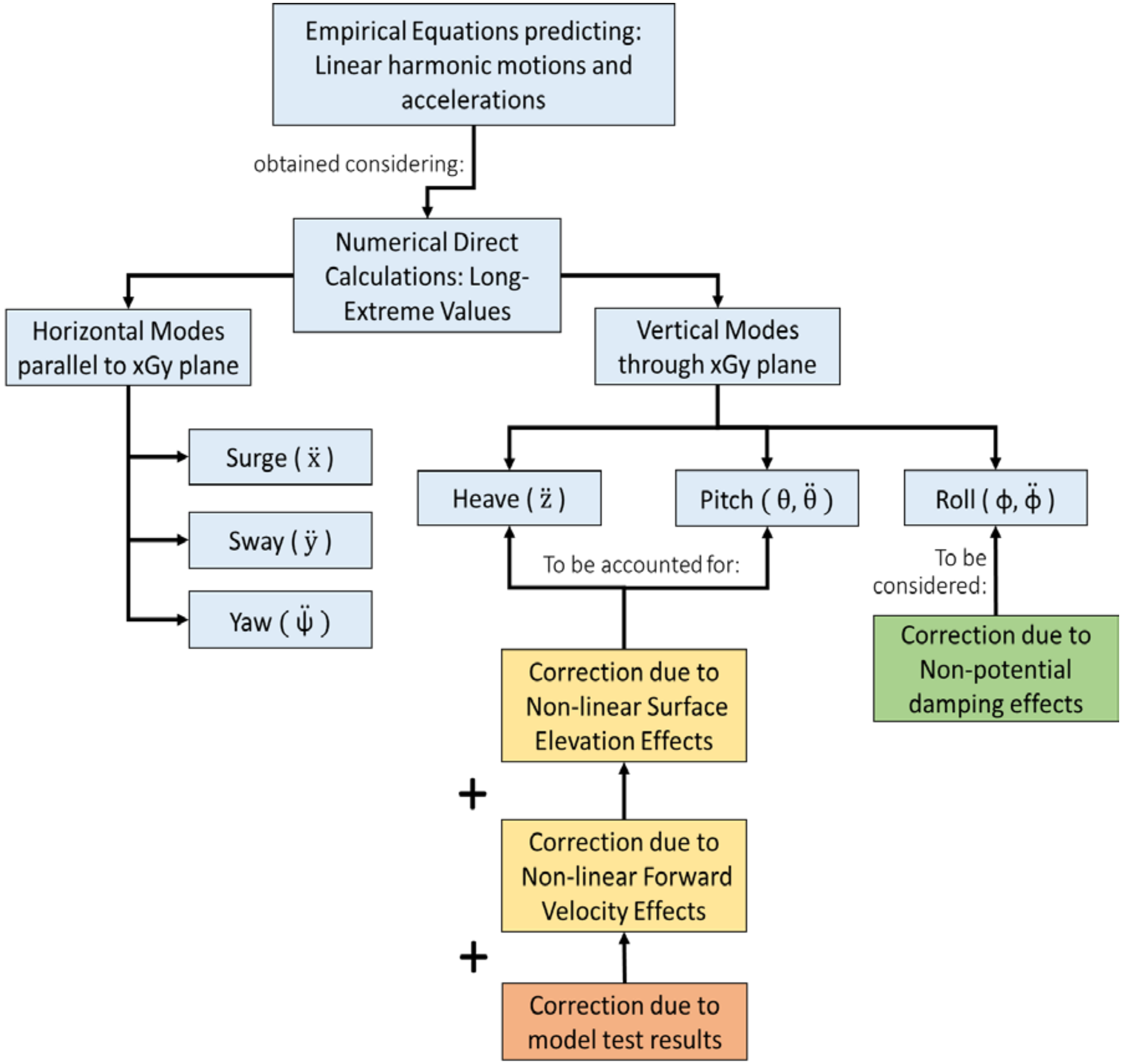
6. Empirical Formulas

Nonlinear Correction

Statistics analysis of ship response in extreme seas, by B. Guo et al. (2016).

In order to see the effect of nonlinear terms:

- Model test results were compared against Numerical nonlinear and linear results;
- 3D Panel method ('nonlinear') and 3D Panel method ('linear') code were used, accordingly;
- Nonlinear simulations were performed in the time domain;
- Linear simulations were performed in the frequency domain;
- Nonlinear Extreme Responses at several V were calculated.



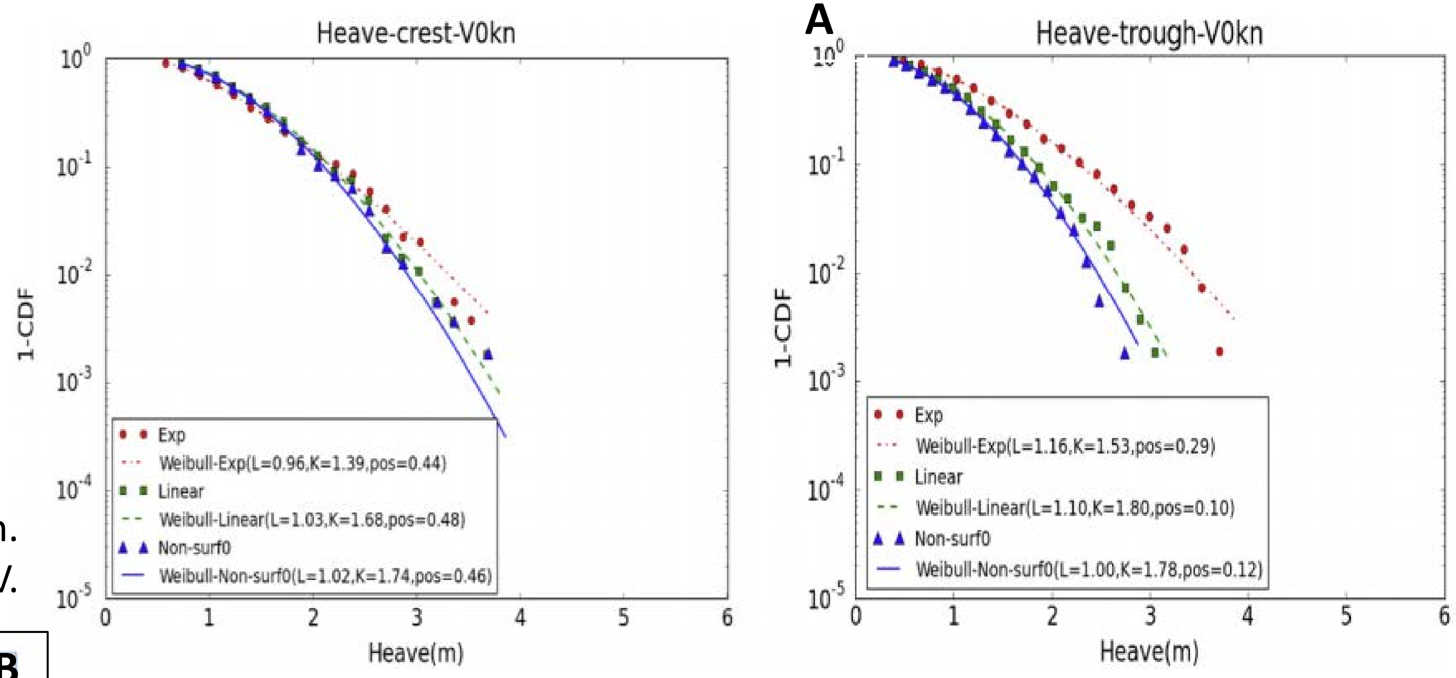
6. Empirical Formulas

Nonlinear Correction

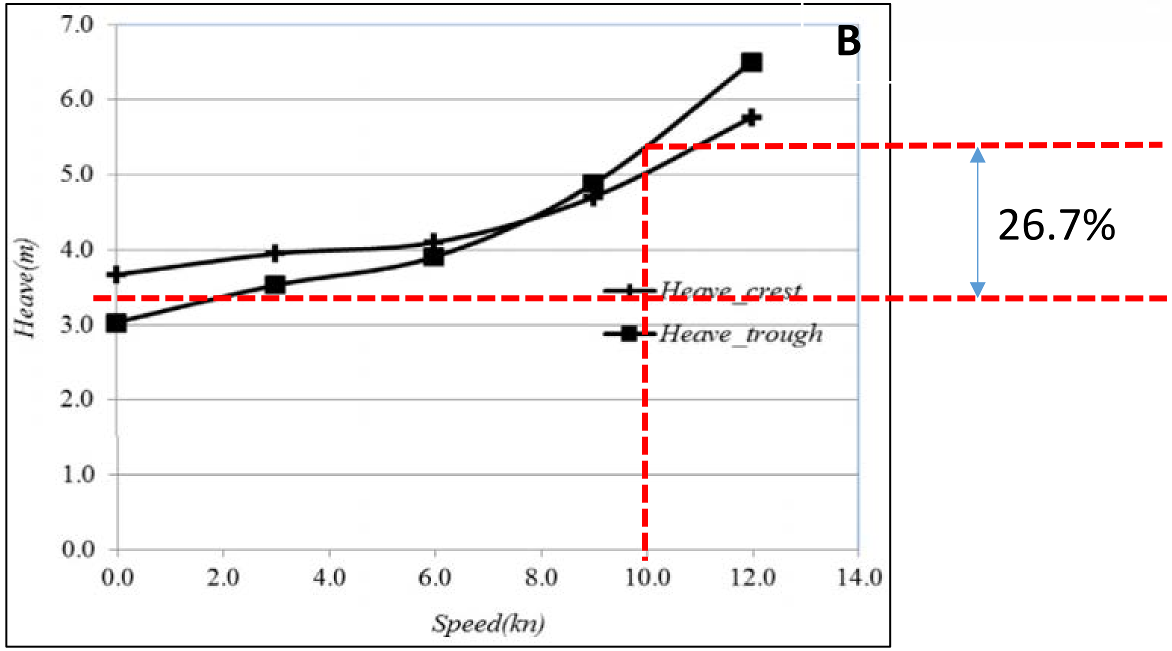
- **Heave mode of motion:**

A: 3-h Statistical representation of Heave Motion.
B: 3-h Heave Extreme value at different V.

A



B



- **Heave Nonlinear Coefficient**

$$\mathrm{fnl_H} = 1.00$$

- **Heave Forward Speed Coefficient**

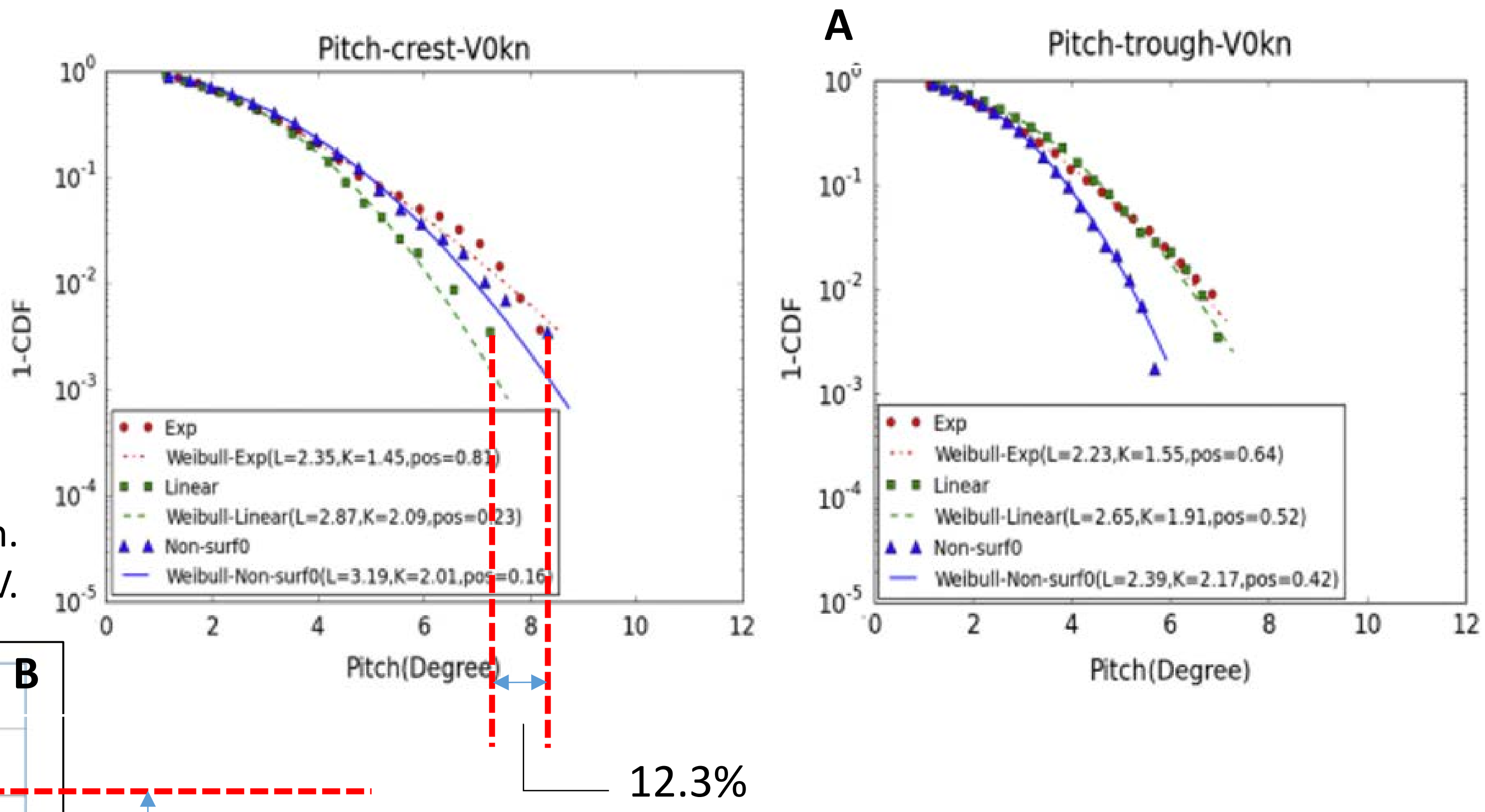
$$\mathrm{fV_H} = 1.58$$

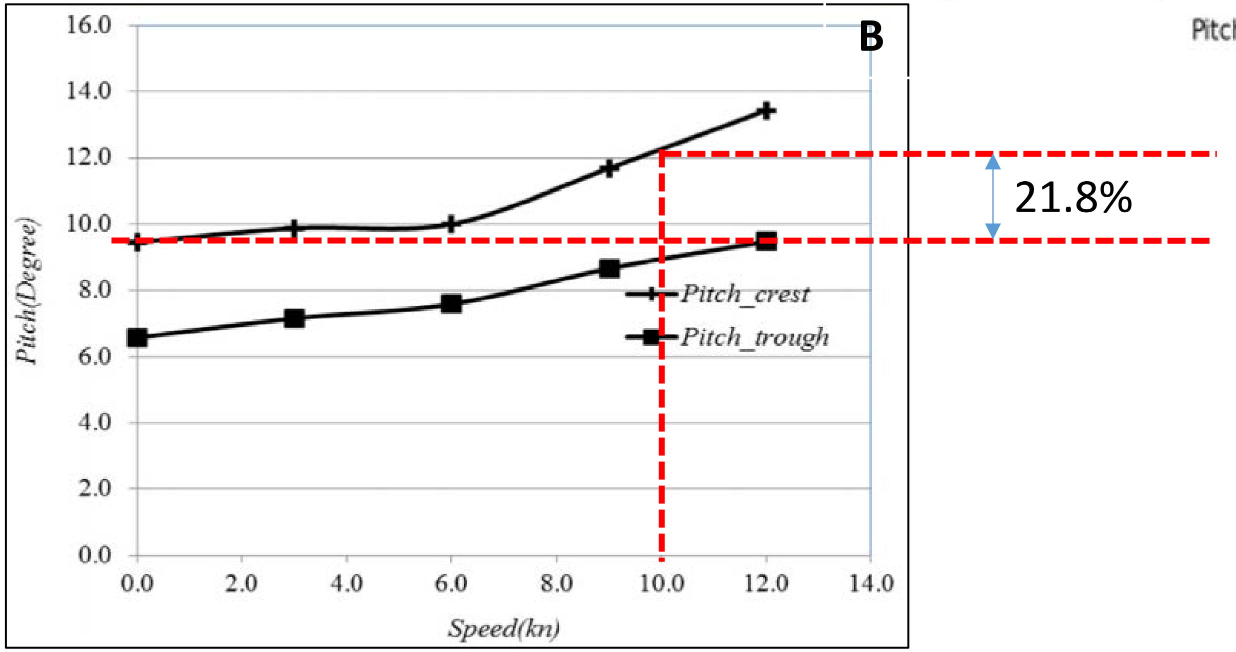
6. Empirical Formulas

Nonlinear Correction

- **Pitch mode of motion:**

A: 3-h Statistical representation of Pitch Motion.
B: 3-h Pitch Extreme value at different V.





- **Pitch Nonlinear Coefficient**

$$\mathrm{fnl_P} = 1.14$$

- **Pitch Forward Speed Coefficient**

$$\mathrm{fV_P} = 1.26$$

6. Empirical Formulas

Nonlinear Correction

- **Relative wave elevation**

  - **Relative wave elevation Nonlinear Coefficient**

$$\mathrm{fnl}_{\mathrm{h1}} = 1.07$$

  - **Relative wave elevation Speed Coefficient**

$$\mathrm{fV}_{\mathrm{h1}} = 1.42$$

7. Conclusions

- The Belgian Coastal Scatter Diagram, under conditions of wave encounter for V = 10 knots, represents an adequate excitation to obtain the maximum long term value that any mode of motion can face.
- Calculating several slopes Entity vs a_B, and plotting them against main ship characteristics (and combinations of them) made possible to find good tendencies for the studied entities. Proposed empirical formulas were developed accordingly.
- Assessment of all **NR217 rules** was carried out, evidencing an underestimation of the values, except for the case of surge acceleration, where the rule proposes a constant value equals to 0.5 m/s^2, representing it a great overestimation.
- Good agreement is achieved between first-order direct calculations and proposed formulas.
- For the range of navigation IN[0.6 < x < 2.0] and the range of wave periods belonging to the Belgian Coastal sea state shown in Fig. 32, nonlinear effects are present.
- Nonlinear corrections were proposed due to Nonlinear wave elevation and Forward Speed Effect.
- Nonlinear corrections come from long-term calculations obtained for a LNG Tanker with C_B equals to 0.7. In consequence, proposed correction should be accounted in the future from inland-vessel simulations considering nonlinear potential theory, for a set of few representative geometries.


Thank you!