Numerical Prediction of the Static Hydrodynamic Derivatives using CFD Techniques

Master Thesis

presented in partial fulfillment
of the requirements for the double degree:
"Advanced Master in Naval Architecture" conferred by University of Liege
"Master of Sciences in Applied Mechanics, specialization in Hydrodynamics, Energetics and Propulsion" conferred by Ecole Centrale de Nantes

developed at "Dunarea de Jos" University of Galati

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Contents

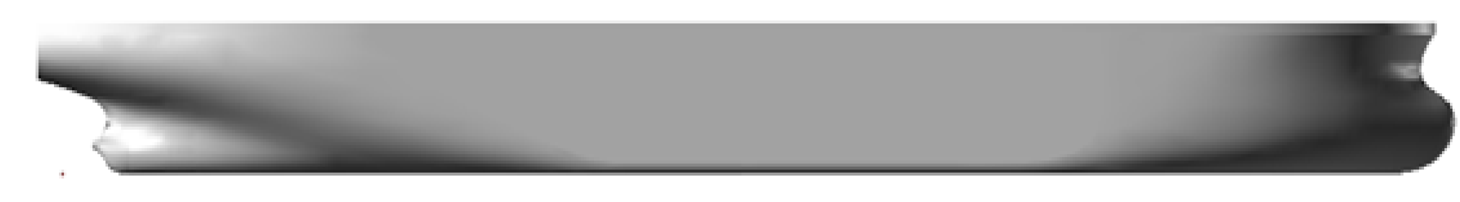
Structure and *goals*

- PHP software platform (ship resistance, powering and manoeuvring performances) of the KVLCC2 ship, in the initial design stage.
- Computational Fluid Dynamic (CFD) techniques :
  - Estimate of ship resistance for bare hull;
  - Calculate the hydrodynamic forces and moment acting on the KVLCC2 hull model in horizontal plan, with the influences of the drift and rudder deflection angles;
- Estimation of the ship trajectories during the turning circle and of Zig-Zag maneuvre
  - Calculate of the static hydrodynamics derivatives
  - Simulate the ship trajectories during the turning circle and Zig-Zag maneuvre

INTRODUCTION

- ✓What is maneuverability;
- ✓What are the related problem;
- ✓How to solve maneuverability problems.

Benchmark

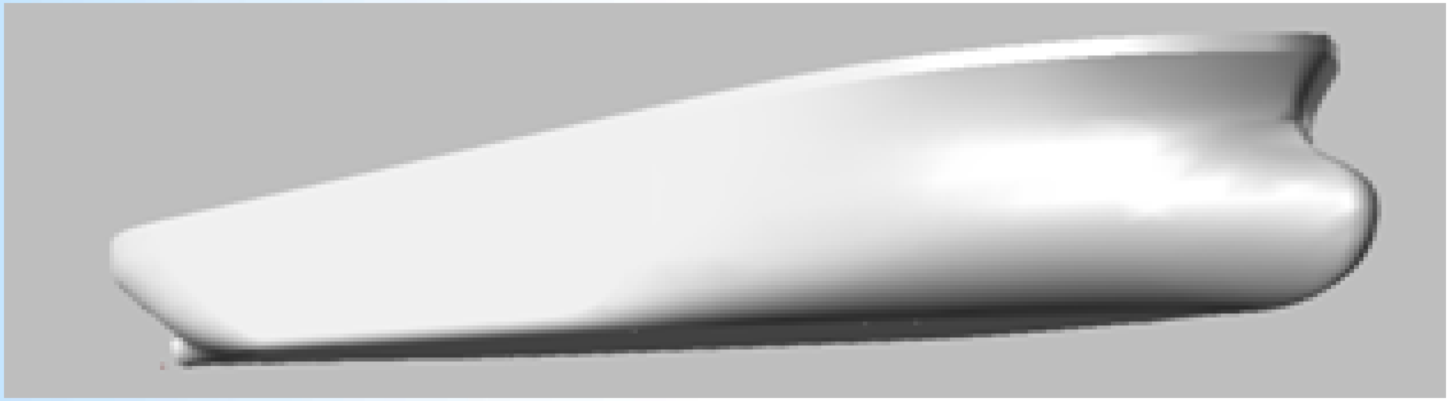


KVLCC2 ship hull

Hull Characteristics	Full scale	model (1/58 scale)
L_{PP} [m]	320,0	5,52
L_{WL} [m]	325,5	5,61
B [m]	58	1
D [m]	30	0,52
T [m]	20,8	0,36
C_B	0,8098	0,8098

Dimension	Value
propeller	
D [m]	9.86
$P/D_{0.7R}$ [m]	0.721
A_E/A_0 [m]	0.431
rudder	
S_R [m^2]	273.3
Projected area [m^2]	136.7

➢Benchmark



KVLCC2 3D hull model

Main particulars	NAPA	Benchmark	Error
Volumetric displacement (m3)	312936,8	312622,0	-0,10%
Wetted surface –without- rudder (m2)	27302,0	27194,0	-0,40%
Block coefficient	0,8085	0,8098	0,16%
Midship section coefficient	0,9980	0,9980	0,00%
LCB (%)	3,442	3,480	1,09%

PRELIMINARY HYDRODYNAMICS PERFORMANCES (USING PHP SOFTWARE PLATFORM)

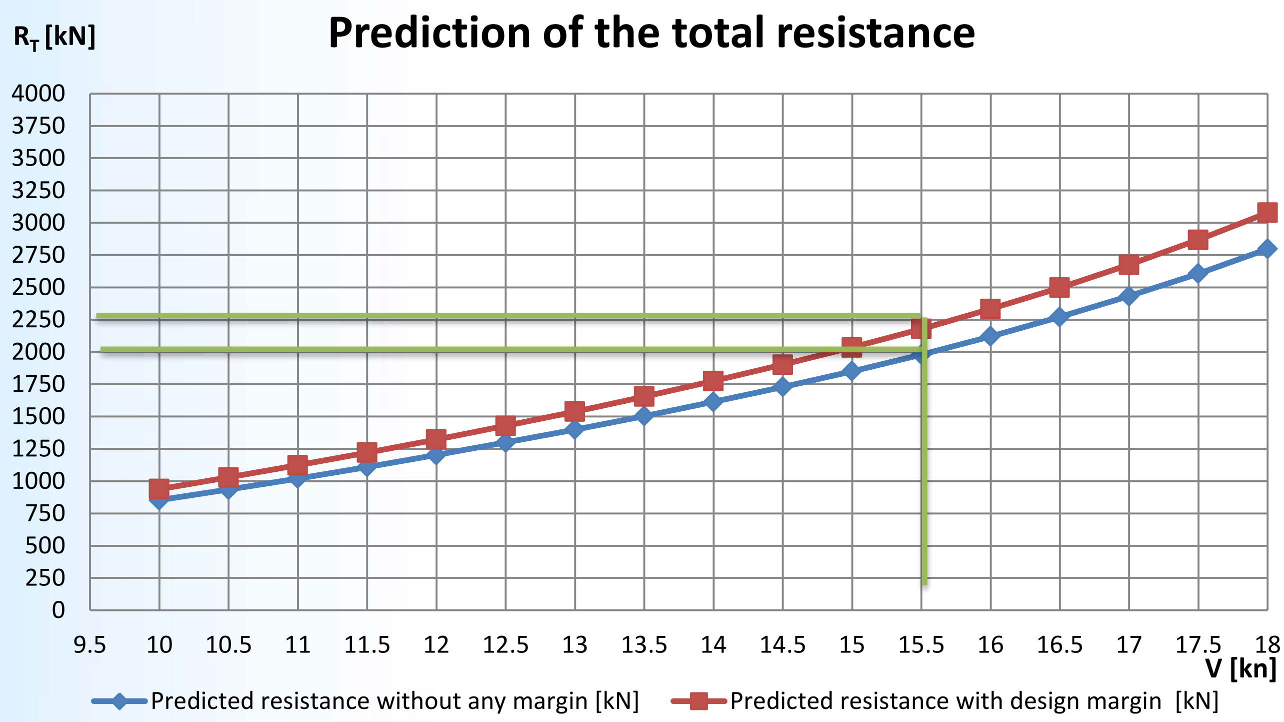
- Resistance;
- Powering;
- Rudder hydrodynamics;
- Manoeuvring performance.

➢Resistance

Holtrop-Mennen method restrictions regarding KVLCC2

Ship Type	Froude number limitation	Cp		L_{WL}/B		B/T	
		Min	Max	Min	Max	Min	Max
Tanker and bulk carriers	Fn<=0,24	0,73	0,85	5,10	7,10	2,40	3,20
Container ships and destroyers	Fn<=0,45	0,55	0,67	6,00	9,50	3,00	4,00
Trawlers, coastal ships and tugs	Fn<=0,38	0,55	0,65	3,90	6,30	2,10	3,00
KVLCC2	0,142	0,81		5,61		2,79	

➢Resistance

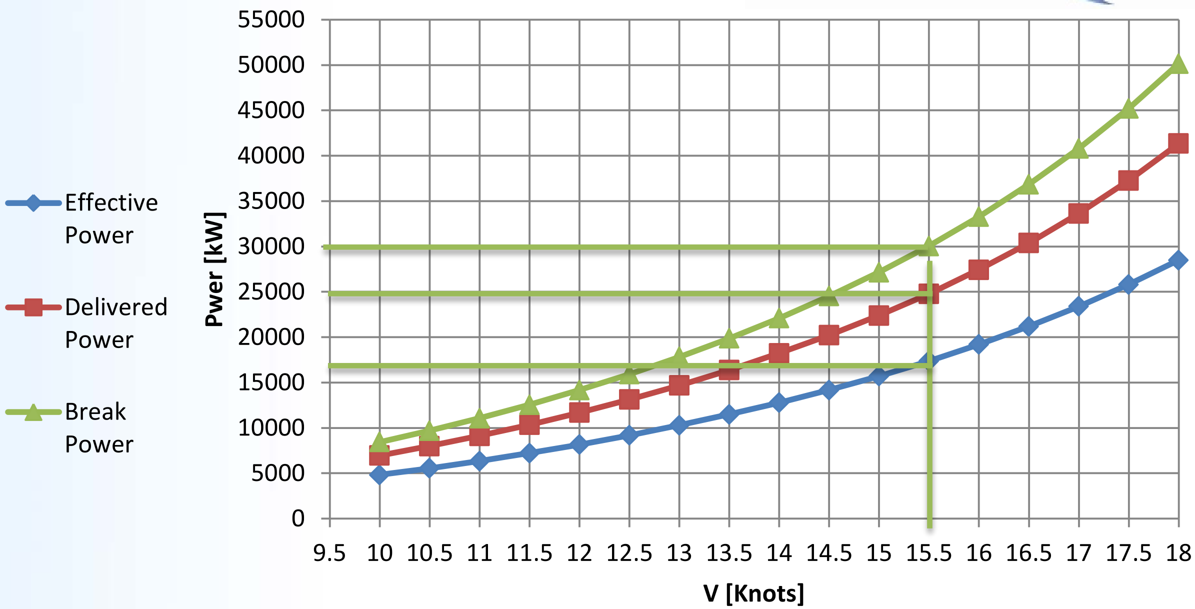


$$R_T' = R_T.(1 + M_D)$$

R_T =1980,14 [kN]

R_T'=2178,15 [kN]

➢Powering



P_E =17368,337 [kW]

P_D =24783,427 [kW]

P_B =30058,735 [kW]

$$P_E = R_T.V.(1+M_D)$$

$$P_D = \frac{P_E}{\eta_D} \qquad P_B = \frac{P_D}{\eta_{th}.(1-M_S)}$$

$$M_S = 0.15\%$$

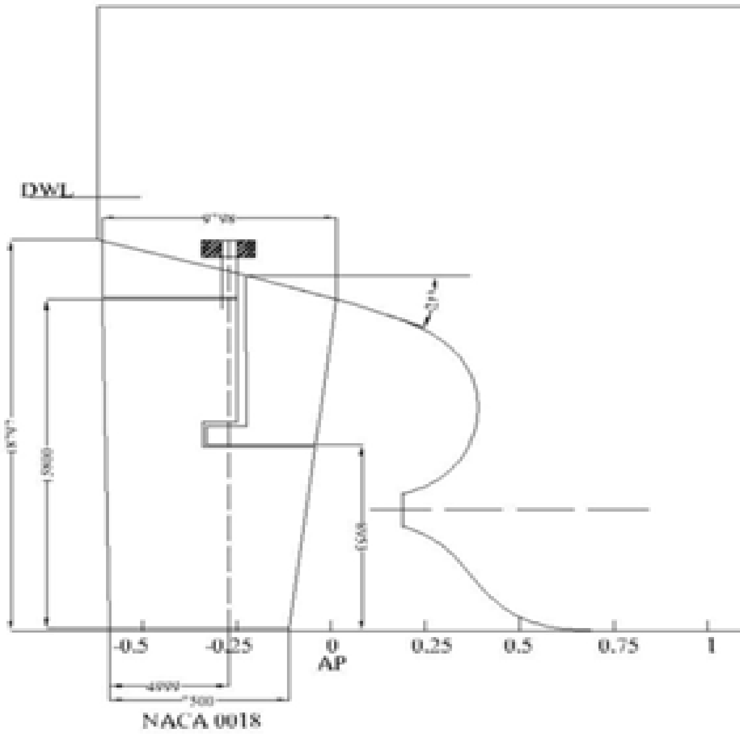
Regression method [kW]	PHP prediction [kW]	Error
P_B=29581,50	P_B=30058,74	1,59%

➢PHP rudder hydrodynamics

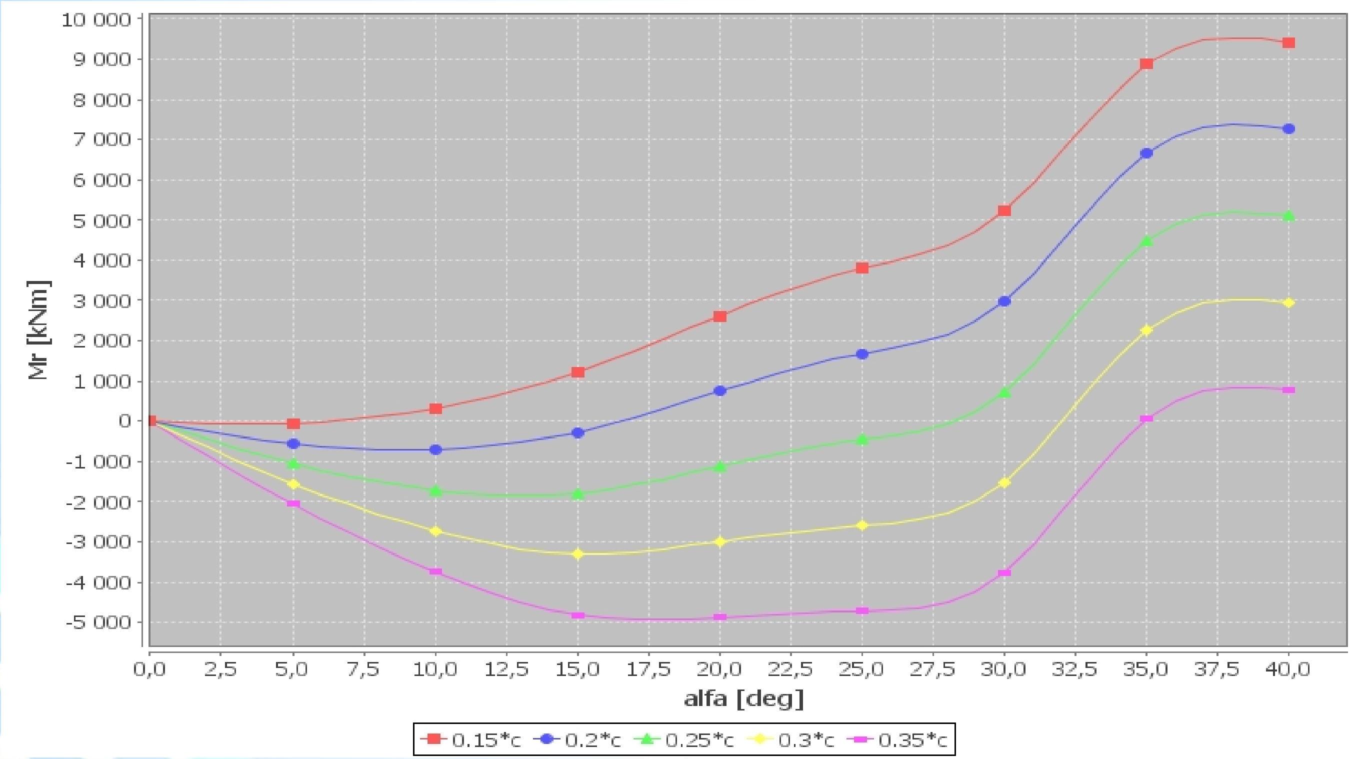
➢Method used

Y.I. Voitkounsky (1985)

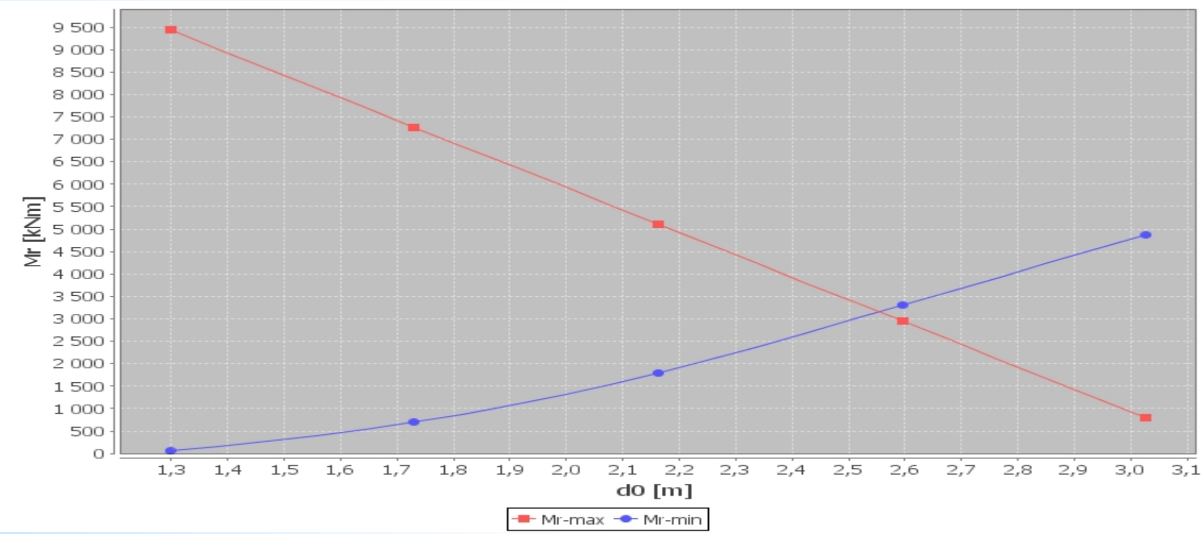
- ✓Ahead and astern ship motions;
- ✓Rudder hydrodynamic forces and moments;
- ✓Optimum position of the rudder stock;
- ✓Maximum value of the torque against the rudder;
- ✓Preliminary checking of the rudder cavitation.



➢PHP rudder hydrodynamics



➢PHP Rudder hydrodynamics



Ahead motion results	
Optimal distance from the rudder stock to the leading edge(d0)	2,553 [m]
Optimal hydrodynamic torque to the rudder stock(MrOpt)	4546,542 [kNm]

Astern motion results	
Distance from the rudder stock to the trailing edge of the rudder (df):	-6,097 [m]
Optimal hydrodynamic torque to the rudder stock in astern motion (MrbOpt):	1952,515 [kNm]

➢PHP rudder hydrodynamics

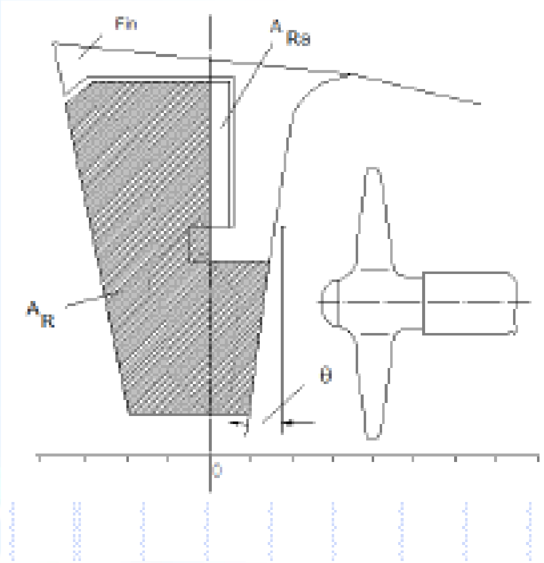
Name	Notation	Ahead	Astern	Unity
Rudder force	C_R	3979,69	723,58	[N]
Rudder torque	M_{TR}	4495,01	1605,59	[kN.m]

Name	Ahead	Astern	Unity
Optimal hydrodynamic torque (PHP software platform)	4546,542	1952,515	[kN.m]
Torque calculations (Bureau Veritas)	4495,01	1605,59	[kN.m]
Error	1,13%	17,77%	

Maximum hydrodynamic torque	4546,542	kNm
Supplementary torque due to the friction	909,308	kNm
Total torque	5455,85	kNm

- PHP Rudder hydrodynamics
- PHP Rudder cavitation

alfa[deg]	pSt [kPa]	pDyn [kPa]	pTot [kPa]
11	221.3	-56,1	165,2 > 0
18	221.3	-104,4	116,9 > 0
22	221.3	-142,9	78,4 > 0



➢Manoeuvring performance

- ✓Abkowitz mathematical model
- ✓Simplified equations in horizontal plane

$$X = m\left(\frac{\partial u}{\partial t} - rv - r^2 x_G\right)$$

$$Y = m\left(\frac{\partial v}{\partial t} + ru + \frac{dr}{dt} x_G\right)$$

$$N = \frac{\partial r}{\partial t} I_{zz} + m x_G\left(\frac{\partial v}{\partial t} + ru\right)$$

Linear mathematical model (Taylor expansion)

$$X_e + X_u u + X_{\dot{u}} \dot{u} = m\dot{u}$$

$$Y_e + Y_v v + Y_r r + Y_{\dot{v}} \dot{v} + Y_{\dot{r}} \dot{r} = m(\dot{v} + rU + \dot{r} x_G)$$

$$N_e + N_v v + N_r r + N_{\dot{v}} \dot{v} + N_{\dot{r}} \dot{r} = I_{zz} \dot{r} + m x_G (\dot{v} + rU).$$

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➢Manoeuvring performance

✓Linear mathematical model

✓Results

•stability parameter C was obtained and presented

C	1.953E-4

•C > 0 ➔ Ship stable on route "

The steady turning diameter value (STD = 2623.3 m) for rudder deflection angle delta = 35 deg.

STD / L	8.059

Yv'	-0.024232
Yvpoint'	-0.015313
Yr'	0.004247
Yrpoint'	-0.001202
Nv'	-0.008382
Nvpoint'	-0.001048
Nr'	-0.003322
Nrpoint'	-0.000799

YdeltaPrime	0.003871
NdeltaPrime	-0.001935

Static derivatives:
on the basis of Clarck

➢Manoeuvring performance

✓Linear evaluation of tuning ability on the basis of Lyster and Knights relations

statistical relations by Lyster and Knights and presented in the following table.

STD / L	2.837	STD	923.428 [m]
TD / L	3.458	TD	1125.493 [m]
AD / L	3.125	AD	1017.046 [m]
TR / L	1.653	TR	538.212 [m]
Vt / Va	0.405	Vt	6.276 [knots]

STD	Steady turning diameter
TD / L	Tactical diameter
AD / L	Advance
TR / L	Transfer
Vt / Va	Speed losses ration

CFD BASED HYDRODYNAMICS PERFORMANCE

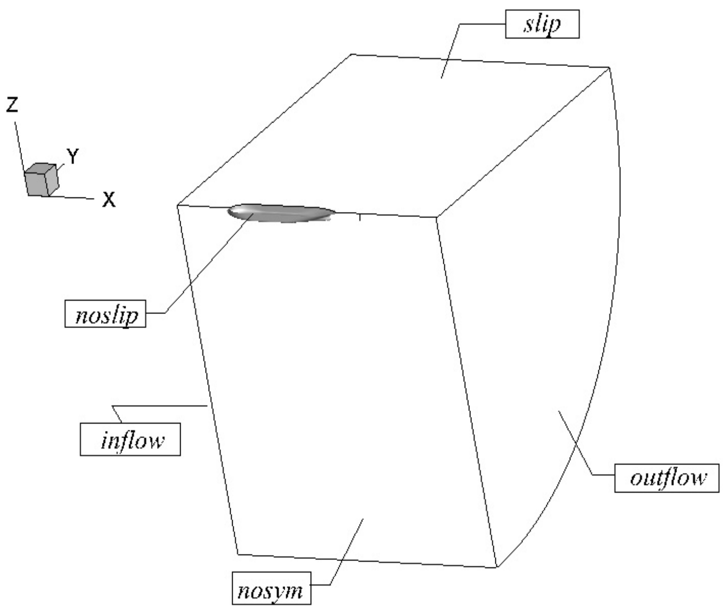
- General overview

  Two configurations were studied:

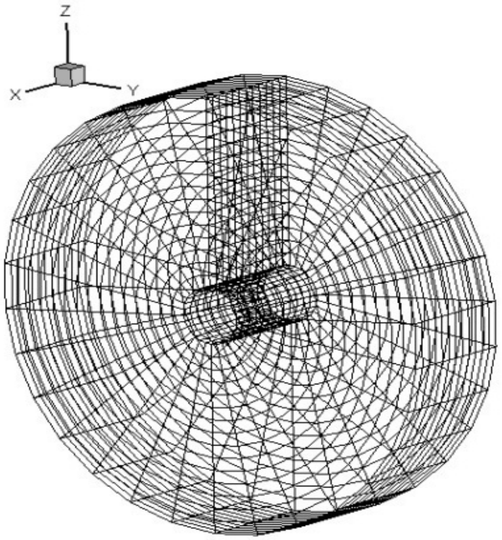
  - Bare hull for ship resistance – potential and viscous flow computation;
  - Equipped hull, a hull with rudder and propeller for static PMM tests – viscous flow computation.

- Mathematical model
  - ✓Potential flow:
  - the flow solution is based on Laplace equation;
  - the boundary condition are imposed on:
    - the hull;
    - the free surface.

- Mathematical model
  - Viscous flow
    - Incompressible fluid;
    - Based on RANS equations;
  - Turbulence model
  - Boundary conditions
    - imposed on all the faces of the computational domain.
      - pressure
      - velocity
      - turbulent kinetic energy
      - turbulent frequency



- Mathematical model
  - ✓ Propeller Model
    - lifting line theory;
    - body force approach.



➢CFD Results

- the 1/58 model scale ship studied by MOERI at SIMMAN 2008

Dimension	Value
L_{pp} [m]	5.5172
B [m]	1.000
d [m]	0.3586
C_B	0.81

Dimension	Value
propeller	
D [m]	0.17
$P/D_{0.7R}$ [m]	0.721
A_E/A_0 [m]	0.431
rudder	
S_R [m^2]	0.0812
Lateral area [m^2]	0.0406

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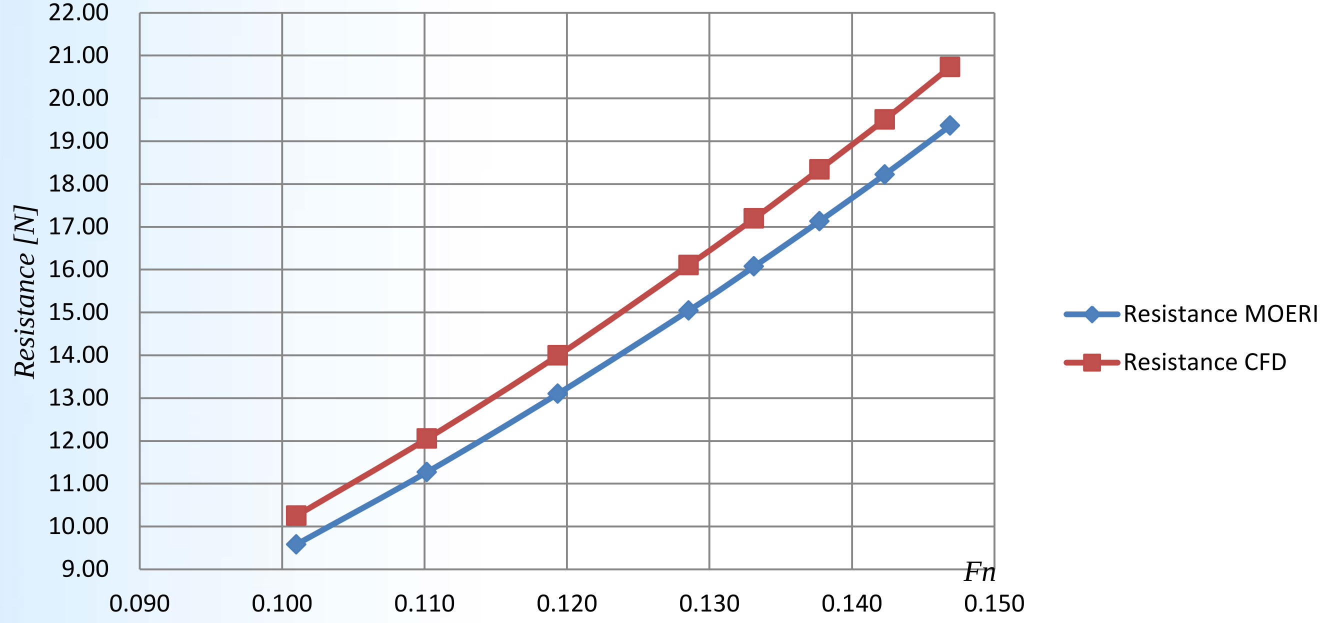
➢Ship resistance modelling conditions:

- Based on the experimental data provided by MOERI ;
- A range of eight speeds between 0.743 to 1.0807 [m/s];
- 1.047 [m/s] model speed corresponds to the 15.5 [Kn] full scale speed;
- all calculations are done for the bare hull model with zero trim angle.

➢Ship resistance results

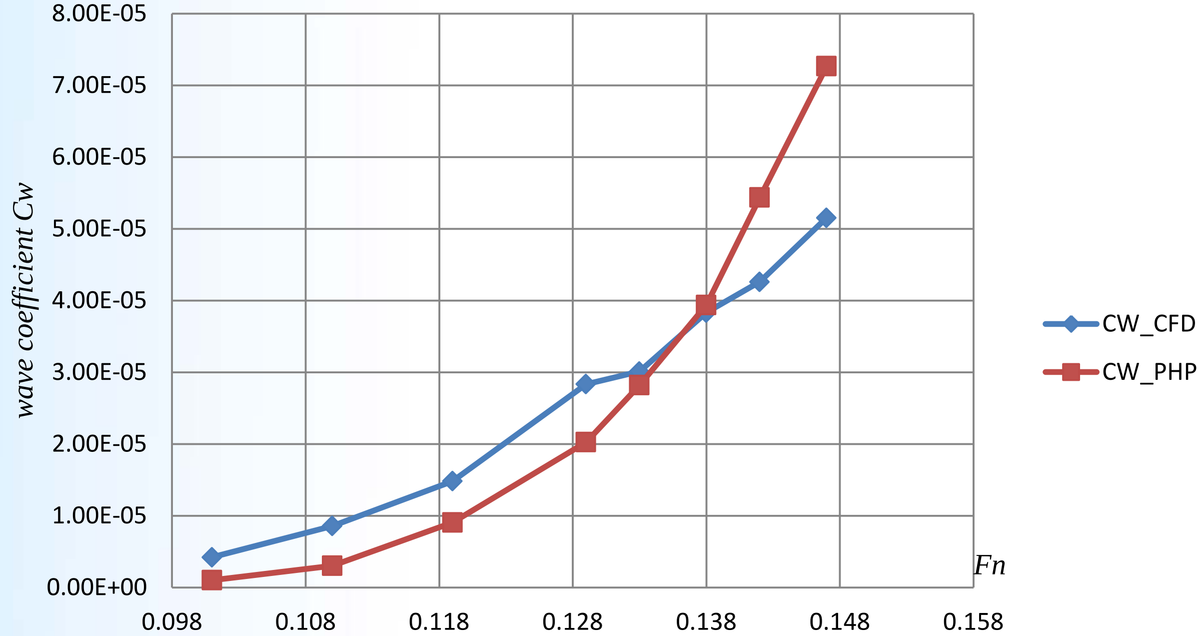


Model Speed [m/s]	$R_{T\ \mathrm{MOERI}}$[N]	$R_{T\ \mathrm{CFD}}$ [N]	*Error %*
0.743	9.58	10.25	7.00%
0.8105	11.27	12.05	6.91%
0.8781	13.10	13.99	6.81%
0.9456	15.04	16.10	7.06%
0.9794	16.07	17.19	6.98%
1.0132	17.13	18.34	7.06%
1.0469	18.22	19.50	7.05%
1,0807	19,36	20,73	7,08%

$$C_T = C_W + C_V = C_W + C_{PV} + C_F$$

$$R_T = C_T \cdot \frac{1}{2} \cdot \rho \cdot U^2 \cdot S$$

➢Ship Resistance results



Fn	C_{W_CFD}	C_{W_PHP}
0.101	4.20 x10^{-6}	1,01 x10^{-6}
0.110	8.56 x10^{-6}	3,02 x10^{-6}
0.119	1.48 x10^{-5}	9,05 x10^{-6}
0.129	2.83 x10^{-5}	2,02 x10^{-6}
0.133	3.01 x10^{-5}	2,82 x10^{-6}
0.138	3.83 x10^{-5}	3,94 x10^{-6}
0.142	4.26 x10^{-5}	5,44 x10^{-6}
0.147	5.15 x10^{-5}	7,27 x10^{-6}

$$\frac{R_w}{R_T} = \frac{0.19}{19.5} = 1\%$$

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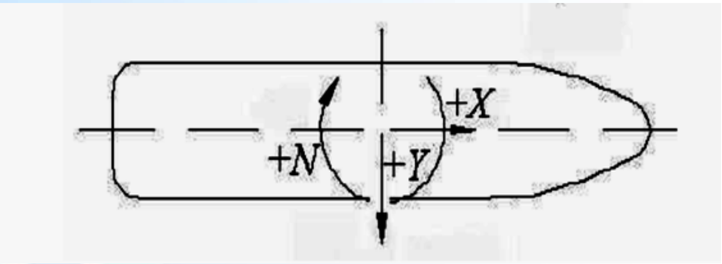
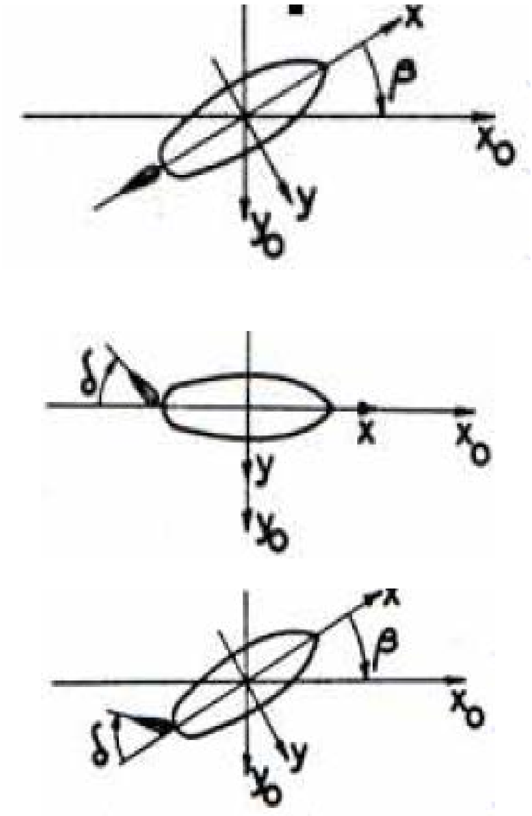
➢Static PMM Tests

- ✓General overview
- ✓Obtain :
  - ✓The longitudinal force, *X*,
  - ✓The transversal force, *Y*,
  - ✓The yaw moment, *N*,





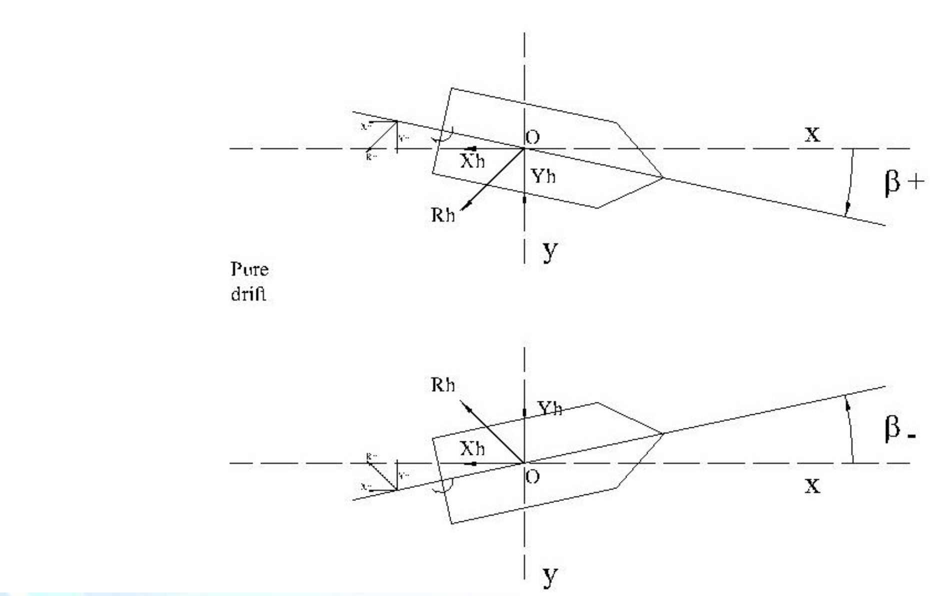
➢Static PMM Tests

✓Modelling Conditions

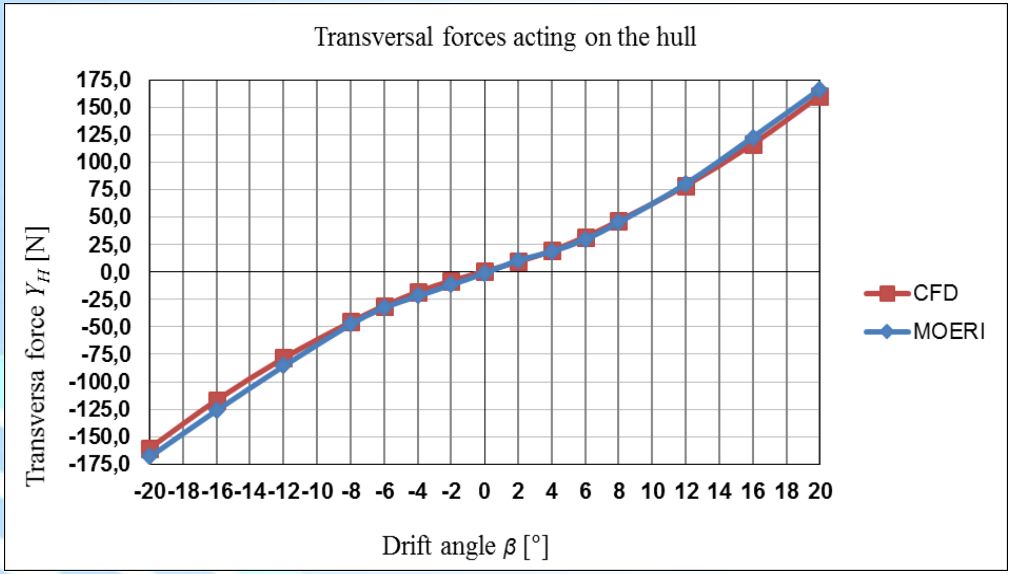
✓Static Drift

➢ The “static drift” numerical tests were done, for a range of drift angles extended between beta = -20° to beta =20° with 2° increment.

➢During all computational tests, the rudder angle was maintained =0°.



➢Static drift tests



β [°]	Y_{H_MOERI}	Y_{H_CFD}	*Error %*
-20	-167.945	-160.351	4.52%
-16	-125.590	-116.479	7.26%
-12	-85.267	-78.212	8.27%
-8	-47.371	-45.496	3.96%
-6	-32.330	-30.679	5.11%
-4	-21.619	-17.931	17.06%
-2	-11.425	-7.991	30.06%
0	-0.779	0.770	-
2	10.791	9.589	11.14%
4	18.881	19.523	-3.40%
6	30.038	32.206	-7.22%
8	45.441	46.816	-3.03%
12	80.648	78.949	2.11%
16	123.035	116.892	4.99%
20	166.701	160.838	3.52%

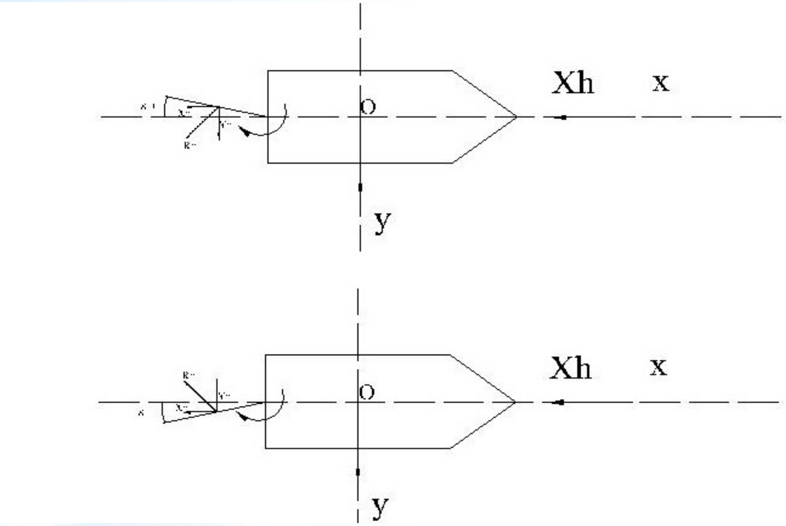
➢Static PMM Tests

✓Modelling Conditions

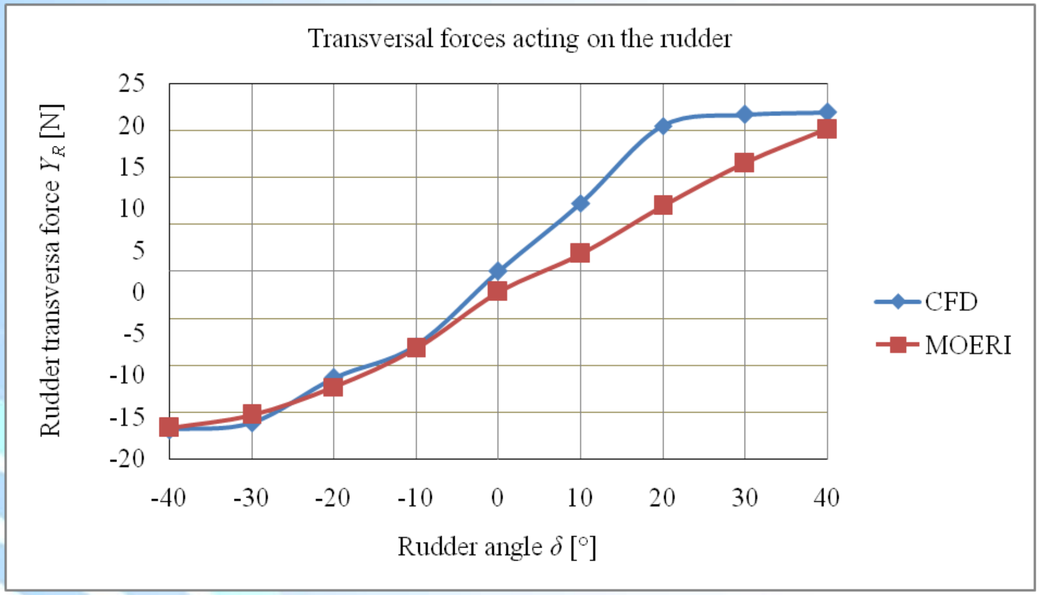
✓Static Rudder

➢The “static rudder” numerical tests were done, for a range of rudder angles extended from delta = -40° to delta =40° with 10° increment.

➢During all computational tests, zero drift angle was maintained, beta =0°.



➢Static Rudder Results



δ [°]	Y_{R_MOERI}	Y_{R_CFD}	Error %
-40	-16.296	-16.903	-3.722
-30	-14.748	-16.195	-9.812
-20	-11.404	-11.359	0.390
-10	-6.743	-7.934	-17.654
0	-	-	-
10	4.606	7.265	-57.734
20	10.334	15.491	-49.898
30	15.458	16.674	-7.866
40	19.499	16.959	13.027

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➢Static PMM Tests

✓Results

✓Static Drift and Rudder

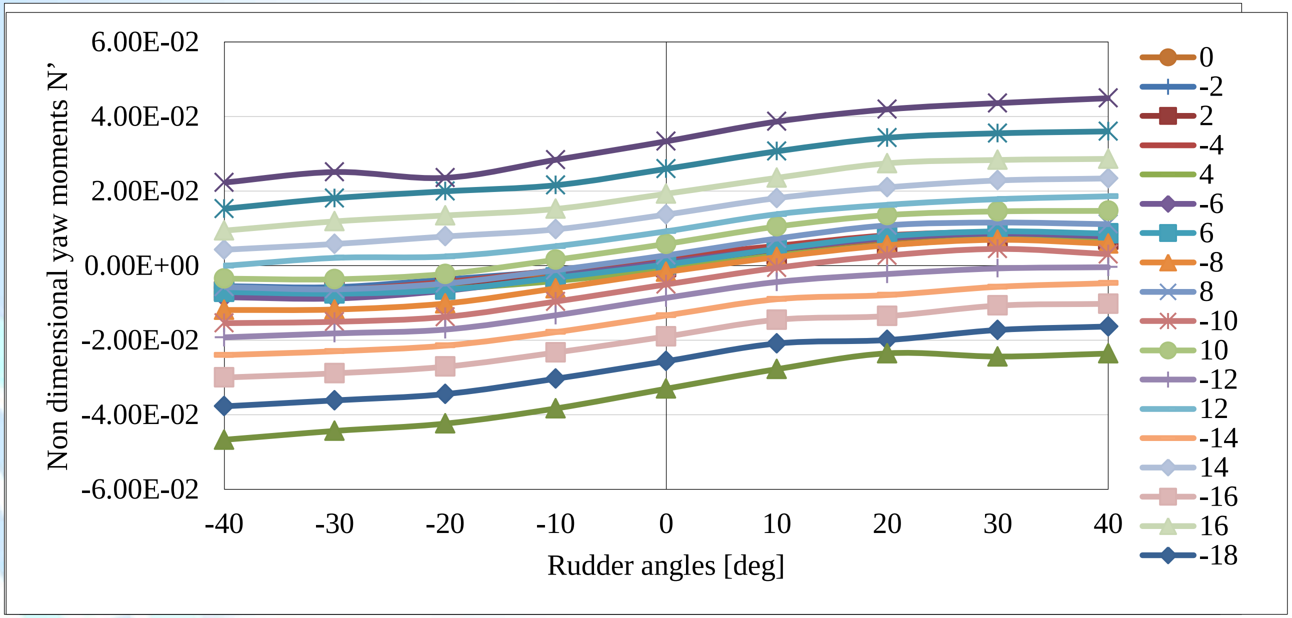
✓analyze the non-dimensional forces and moment obtained by the use of the following formulas:

$$\frac{Force}{0.5\rho U^2 L_{wL}^2} \qquad \frac{Moment}{0.5\rho U^2 L_{wL}^3}$$

➢Static PMM Tests

✓Results

✓Non dimensional forces and moment



Simulation of the turning circle and Zig-Zag maneuver

- Introduction
  - The static hydrodynamics derivatives obtained
  - Turning circle and Zig-Zag maneuver trajectories will be simulated.

- Static hydrodynamic derivatives
  - Used computer code POLYNEW developed at “Dunarea de Jos” University of Galati.
  - Input data the non-dimensional hydrodynamic forces and moments obtained from CFD “static drift and rudder” results,

➢static hydrodynamic derivatives

- ➢Results
- ➢Non dimensional derivatives

Xu point = $m - X_{\dot{u}}$	Clarke	Xvr= $X_{vr} + m$	0
Xvv=1/2 X_{vv}	CFD-static tests	Xvd= $X_{v\delta}$	CFD-static tests
Xrr=1/2 $X_{rr} + mx_G$	0	Xrd= $X_{r\delta}$	0
Xdd=1/2 $X_{\delta\delta}$	CFD-static tests	X0= X_0	0

Qvdot= $mx_G - N_{\dot{v}}$	Clarke	Qrdd=1/2 $N_{r\delta\delta}$	0
Qrdot= $I_{zz} - N_{\dot{r}}$	Clarke	Qd= N_{δ}	Clarke
Qv= N_v	Clarke	Qddd=1/6 $N_{\delta\delta\delta}$	CFD-static tests
Qvvv=1/6 N_{vvv}	CFD-static tests	Qdvv=1/2 $N_{\delta vv}$	CFD-static tests
Qvrr=1/2 N_{vrr}	0	Qdrr=1/2 $N_{\delta rr}$	0
Qvdd= $\frac{1}{2} N_{v\delta\delta}$	CFD-static tests	Qdu= $N_{\delta u}$	0
Qr= $N_r - mx_G U$	Clarke	Qvrd= $N_{vr\delta}$	0
Qrrr=1/6 N_{rrr}	0	Q0= N_0	0
Qrvv=1/2 N_{rvv}	0	Q0u= N_{0u}	0

Yvdot= $m - Y_{\dot{v}}$	Clarke	Yrdd=1/2 $Y_{r\delta\delta}$	0
Yrdot= $mx_G - Y_{\dot{r}}$	Clarke	Yd= Y_{δ}	Clarke
Yv= Y_v	Clarke	Yddd=1/6 $Y_{\delta\delta\delta}$	CFD-static tests
Yvvv=1/6 Y_{vvv}	CFD-static tests	Ydvv=1/2 $Y_{\delta vv}$	CFD-static tests
Yvrr=1/2 Y_{vrr}	0	Ydrr=1/2 $Y_{\delta rr}$	0
Yvdd=1/2 $Y_{v\delta\delta}$	CFD-static tests	Ydu= $Y_{\delta u}$	0
Yr= $Y_r - mU$	Clarke	Yvrd= $Y_{vr\delta}$	0
Yrrr=1/6 Y_{rrr}	0	Y0= Y_0	0
Yrvv=1/2 Y_{rvv}	0	Y0u= Y_{0u}	0

- Turning circle results
  - Stability on route
    - Using CFD Techniques;
    - static derivatives were performed;
    - stability parameter C was obtained and presented

C	-2,092E-05

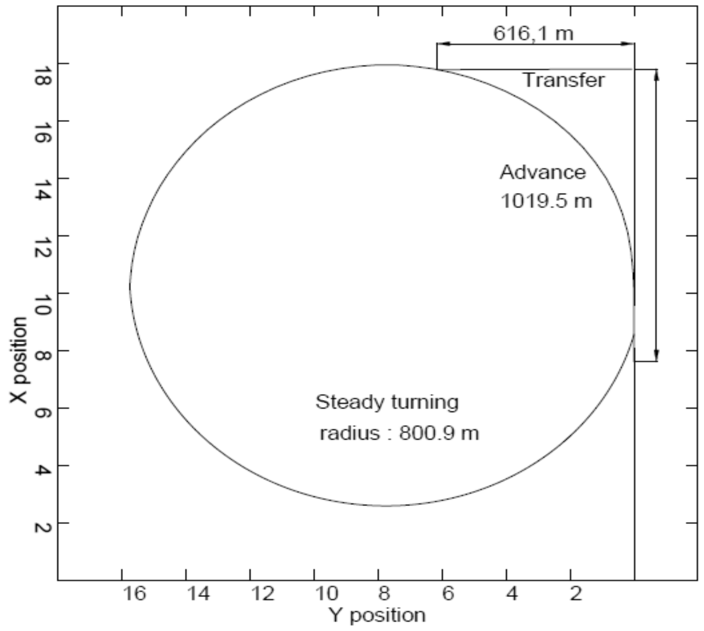
- C < 0 ➔ Ship not stable on route

➢Turning circle simulation

✓Using the PMMPROG simulation code, the turning circle parameters with rudder deflection angle 35 ° have been obtained.

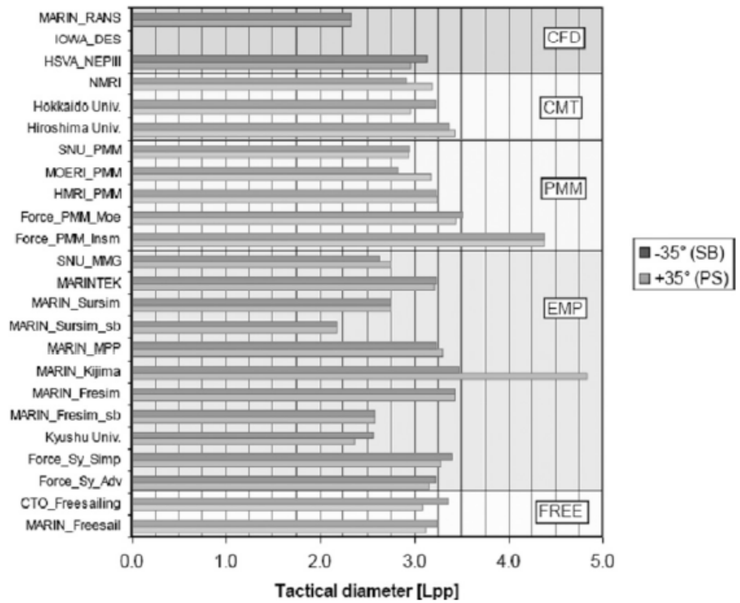
TURNING CIRCLE PARAMETERS

rudder angle [deg].............. 35.0
advance -90 deg- [m]........... 1019.5
transfer -90 deg- [m]........... -616.1
max advance [m]................. 1035.2
tactical diameter [m]........... 1558.8
time for change 90 deg [sec]... 198.0
time for change 180 deg [sec]... 438.0
max transfer [m]................ -1575.7
steady turning radius [m]....... 800.9
steady drift angle [deg]........ -11.9
final speed [kn]................ 8.80



STD / L	4,921	STD	1601,8 [m]
TD / L	4,789	TD	1558,8 [m]
AD / L	3,132	AD	1019,5 [m]
TR / L	1,893	TR	616,1 [m]
Vt / Va	0,568	Vt	8,8 [kn]

STD	Steady turning diameter
TD	Tactical diameter
AD	Advance
TR	Transfer
Vt / Va	Speed losses ration



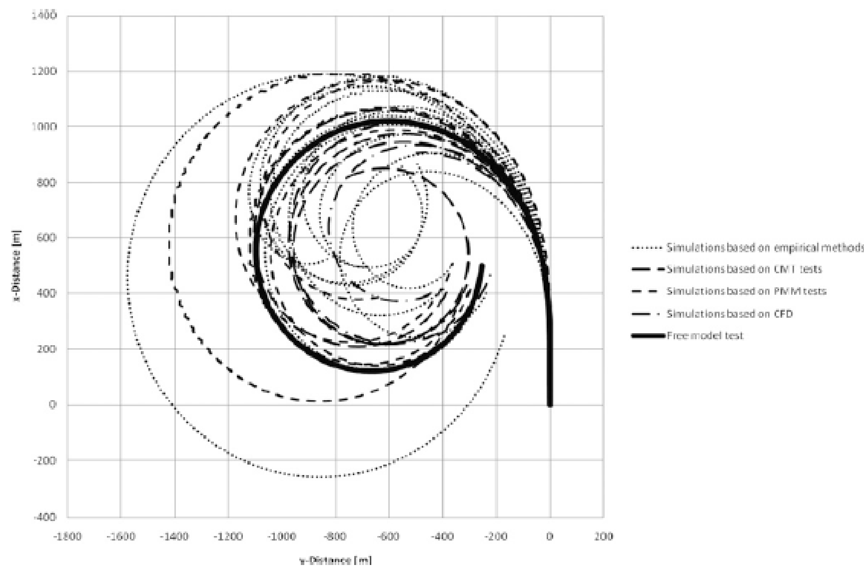
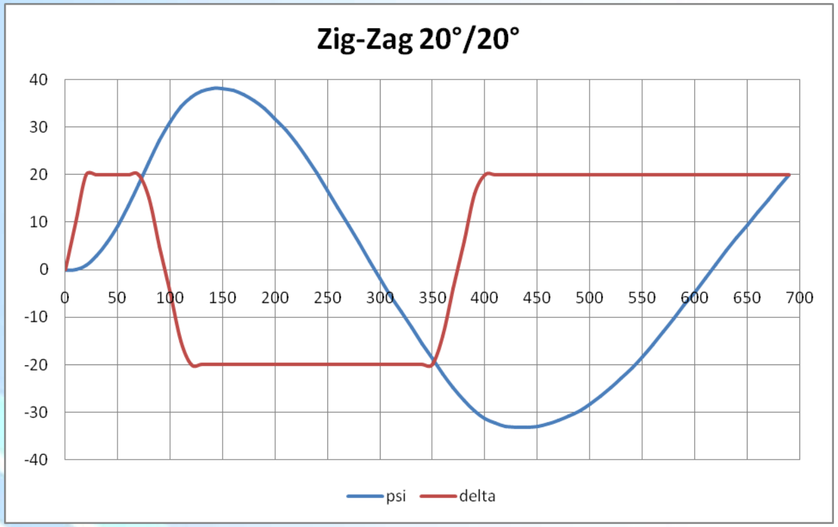


Fig. 5 KVLCC1 simulations of 35 deg turning circle to port side

STD Min= 2.1
STD Max= 4.9
STD UGAL= 4.9

➢ Zig-Zag simulations



First overshoot angle (Zig-Zag 20°/20°)	18,2
Second overshoot angle (Zig-Zag 20°/20°)	13,2
Initial turning time, ta	70’
Advance (reach) Ts	295’
Period	620’

➢Turning circle and Zig-Zag simulations

➢In order to check the ship manoeuvring performances, the IMO standard manoeuvres criteria presented in Table were applied.

Standard manoeuvre	Characteristics	Maximum values	Obtained values	Criteria
Turning circle	Advance (AD)	≤ 4,5 L	3,1	Passed
	Tactical diameter (TD)	≤ 5 L	4,8	Passed
Zig-Zag manoeuvre	First overshoot angle (Zig-Zag 20°/20°)	≤25’	18,2’	Passed

➢It is seen that all the criteria are fulfilled.

➢Conclusion

Maneuver characteristics	Initial design method		Basic design method (Simulation codes with CFD hydrodynamic derivatives)
	Linear model	statistic method	Non linear method
Stability on route	1,95E-04	None	-2,09E-05
STD/L	8,059	2,837	4,921
TD/L	None	3,458	4,789
AD/L	None	3,125	3,132
T/L	None	1,653	1,893
First overshoot angle (Zig-Zag 20°/20°)	None	None	18,2’
Second overshoot angle (Zig-Zag 20°/20°)	None	None	13,2’

Conclusion

- The CFD is a very important tool at into initial design stage or basic design;

Future works

- The static derivatives are not sufficient
- necessary to obtain and to use other important dynamic derivatives by means of the CFD Techniques;
- Grid study for rudder can be developed.

Thank you very much !!!