Numerical Investigation of the Hydrodynamic Performances of Marine Propeller

Carlos Parra

Master Thesis

developed at "Dunarea de Jos" University of Galati

in the framework of the

"EMSHIP"
Erasmus Mundus Master Course
in "Integrated Advanced Ship Design"

Supervisor: Professor Mihaela Amoraritei

Gdynia, February 2013

Motivation

- Increase my knowledge in propeller design
- As a complement of the normal propulsion lectures
- Solving a real case of propulsion problem

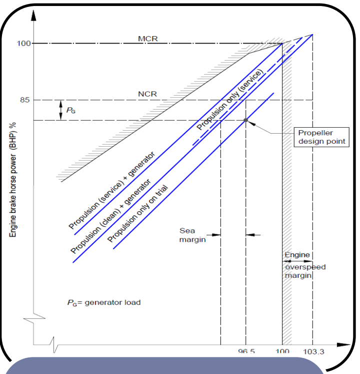
- Understand the Lifting-line method with surface corrections
- Developing strategies in CFD propeller analysis

- Final aim: to decrease the dependance of the towing tank test and cavitation tunnels.

Contents

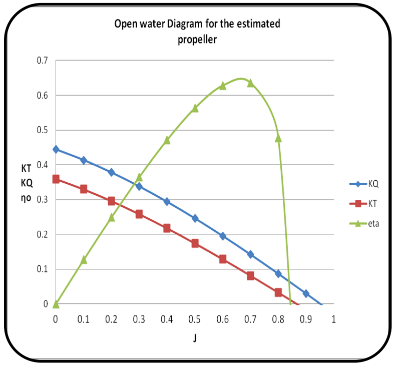
- Propeller design methodology: Stages
- Definition of the problem: Given information
- Starting point: Optimum diamater and efficiency η_o
- Lifting-Line theory: Geometry of propeller and Thrust
- Numerical Analysis instead of Experimental test
- Results

PROPELLER DESIG STAGES



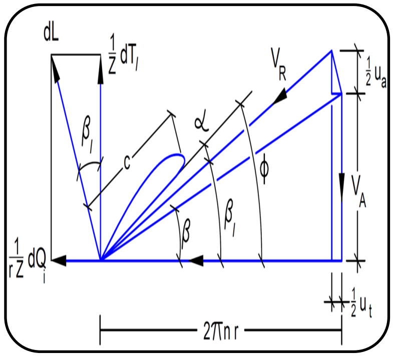
Definiton of problem

- Propeller design point
- VS
- PB
- r.p.m./r.p.s.
- Z
- AE/Ao
- D=???



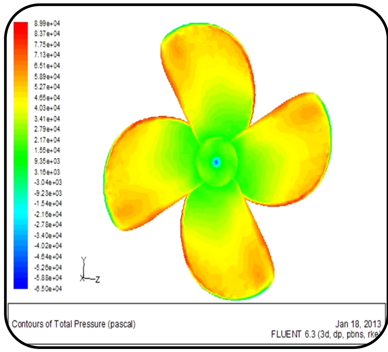
First Stage: Preliminary Design

- Dopt
- Optimal ηo
- Wageningen-B series Diagrams



Second Stage: Design

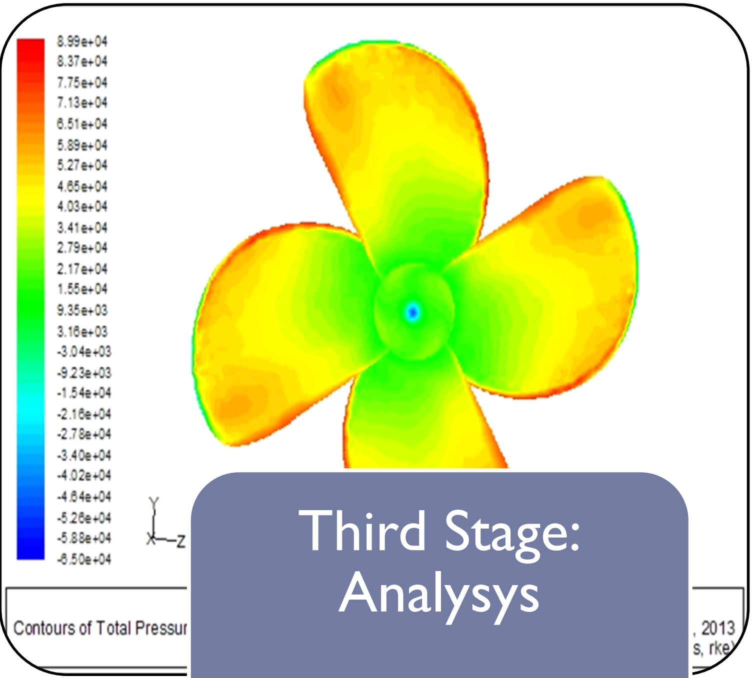
- Lifting-line theory



Third Stage: Analysys

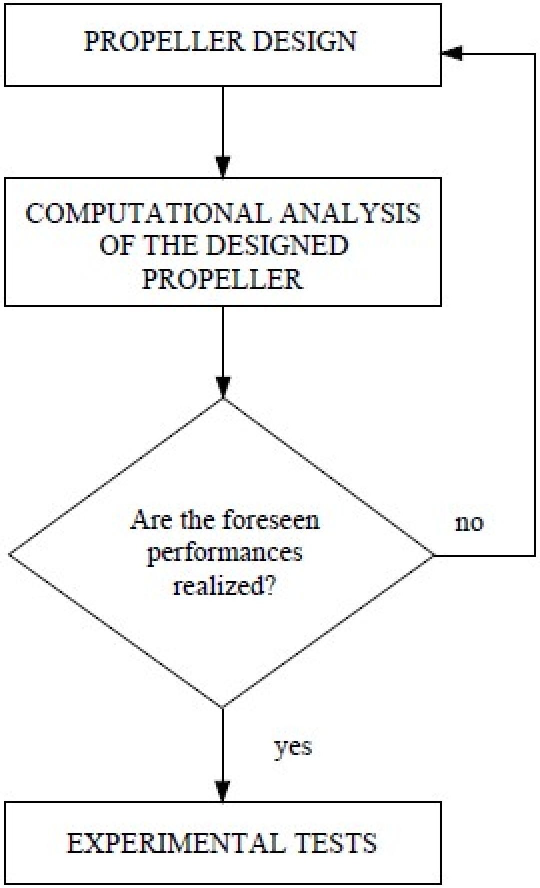
- Towing tank
- Cavitation tunnel
- Numerical Analysis

PROPELLER DESIG STAGES



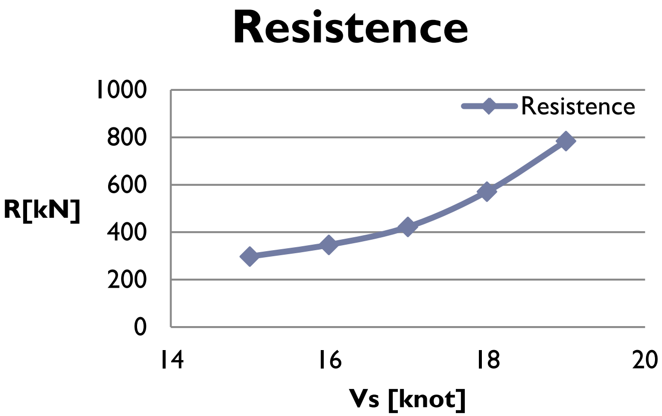
Third Stage: Analysys

- Towing tank
- Cavitation tunnel
  - or
- Numerical Analysis



Definition of the problem

V_S	knot	17.4
Lpp	m	125
B	m	21.4
T	m	8.5
Volume	m³	14758
Engine type	-	MAN B&W 5 S46ME
Break Power	kW	6900 MCR
RPM	-	129
ηshaft	-	0.98
w		0.3144
t		0.2125
Z		4



R_T =476.08[kN]

$$T = \frac{R_T}{(1-t)} = 604.55\ [\mathrm{kN}]$$

$$P_D = P_B \cdot \eta_{shaft}(1-SM)$$

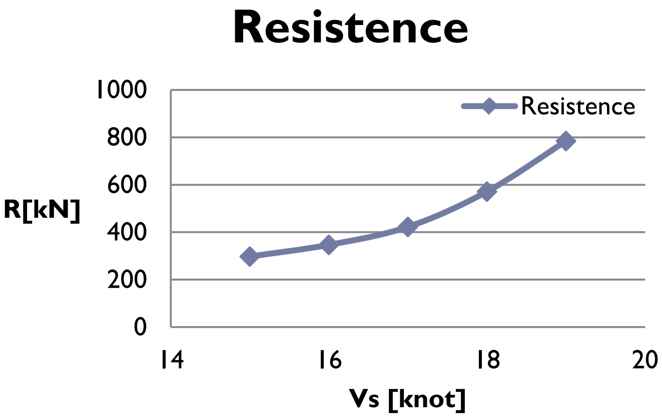
P_D= 5747.7 [kW]

$$\frac{A_E}{A_O} = \frac{(1.3+0.3Z)T}{(po-pv)D^2} + k = 0.6$$

$$C_{Th} = \frac{T}{\rho V_A^2 D^2 \frac{\pi}{8}} = 0.71$$

Definition of the problem

V_S	knot	17.4
Lpp	m	125
B	m	21.4
T	m	8.5
Volume	m³	14758
Engine type	-	MAN B&W 5 S46ME
Break Power	kW	6900 MCR
RPM	-	129
ηshaft	-	0.98
w		0.3144
t		0.2125
Z		4



R_T =476.08[kN]

$$P_D = P_B \cdot \eta_{shaft}(1 - SM)$$

$$T = \frac{R_T}{(1-t)} = 604.55\ [kN]$$

P_D= 5747.7 [kW]

$$\frac{A_E}{A_O} = \frac{(1.3 + 0.3Z)T}{(po - pv)D^2} + k = 0.6$$

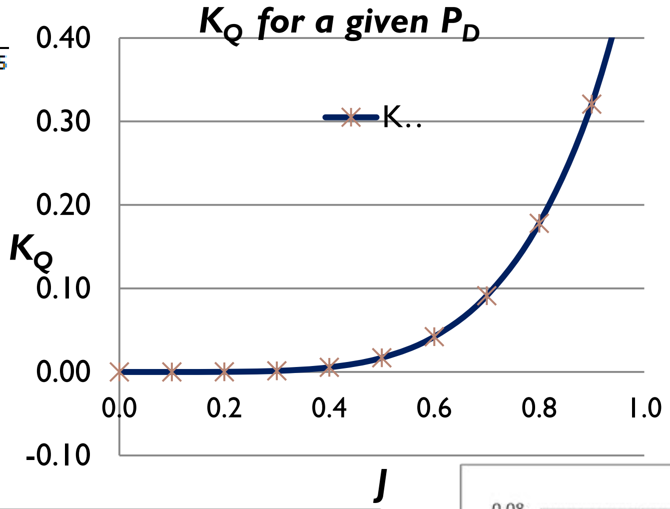
Absorb the minimum power PD at certain Ship speed !!!

Preliminary design

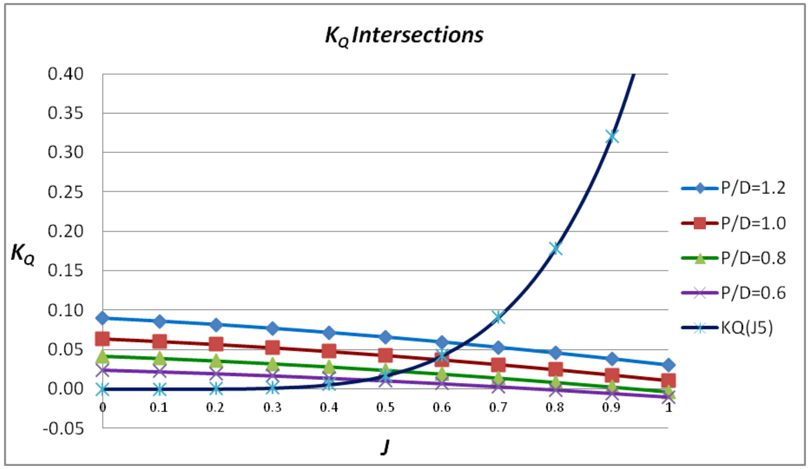
$$K_Q = \frac{Q}{\rho \cdot n^2 \cdot D^5} = \frac{P_D}{2\pi \cdot \rho \cdot n^3 \cdot D^5}$$

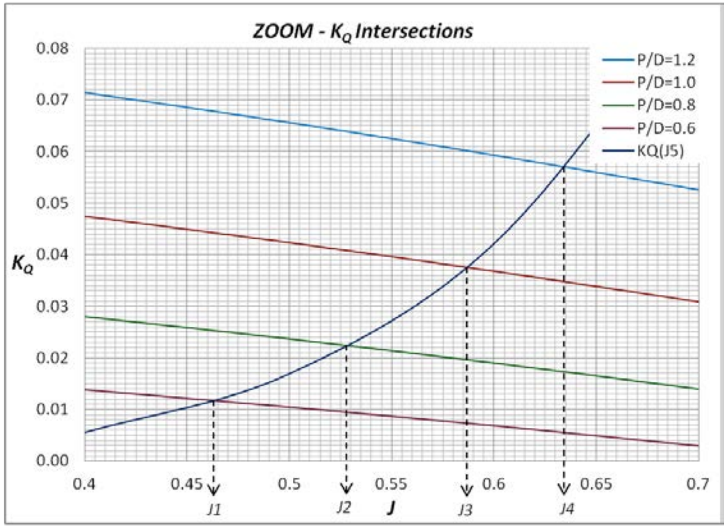
$$J = \frac{V_A}{n \cdot D}$$

$$\frac{K_Q}{J^5} = \frac{P_D \cdot n^2}{2\pi \cdot \rho \cdot V_A^5}$$



$$K_Q = \left(\frac{P_D \cdot n^2}{2\pi \cdot \rho \cdot V_A^5}\right) \cdot J^5$$



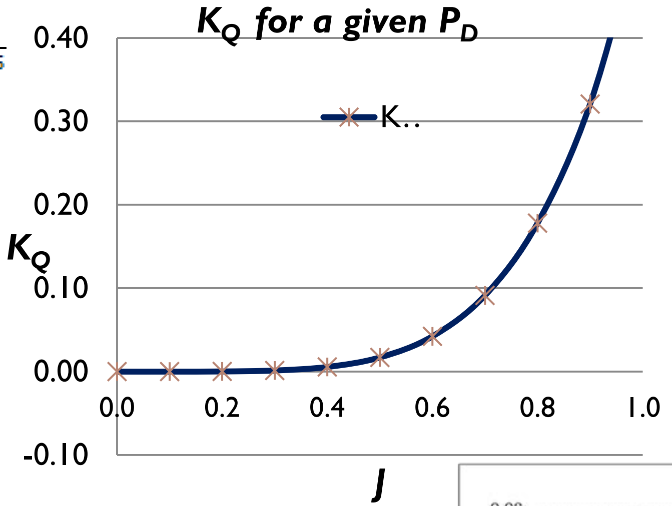


Preliminary design

$$K_Q = \frac{Q}{\rho \cdot n^2 \cdot D^5} = \frac{P_D}{2\pi \cdot \rho \cdot n^3 \cdot D^5}$$

$$J = \frac{V_A}{n \cdot D}$$

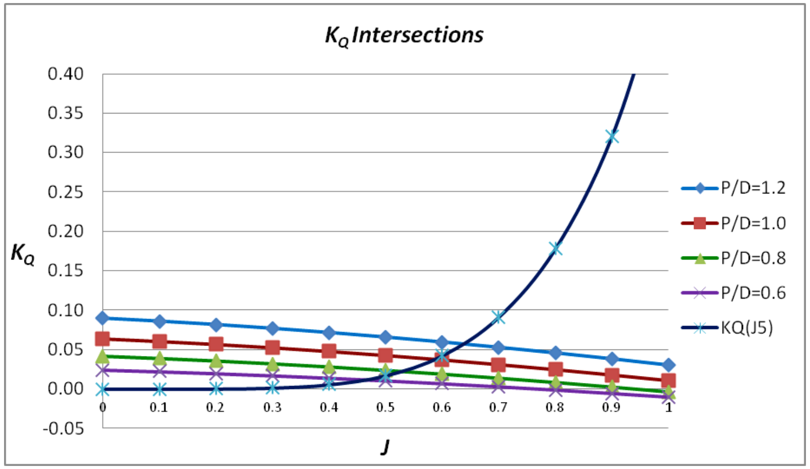
$$\frac{K_Q}{J^5} = \frac{P_D \cdot n^2}{2\pi \cdot \rho \cdot V_A^5}$$

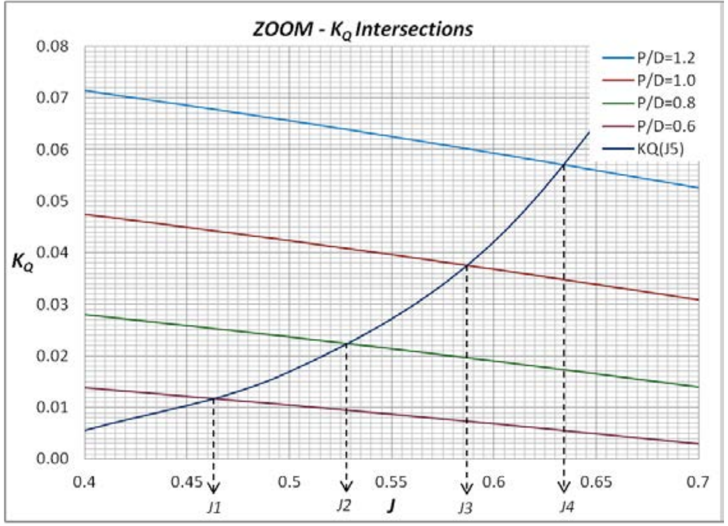


$$K_Q = \left(\frac{P_D \cdot n^2}{2\pi \cdot \rho \cdot V_A^5}\right) \cdot J^5$$

Polynomials form of K_Q

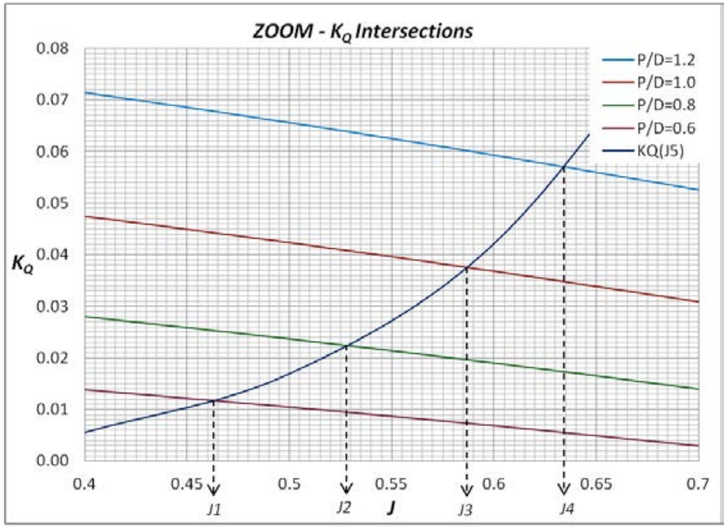
$$K_Q = \sum_{n=1}^{47} Cn\,(J)^{Sn}\,(P/D)^{tn}\,(A_E/A_o)^{un}\,(Z)^{vn}$$



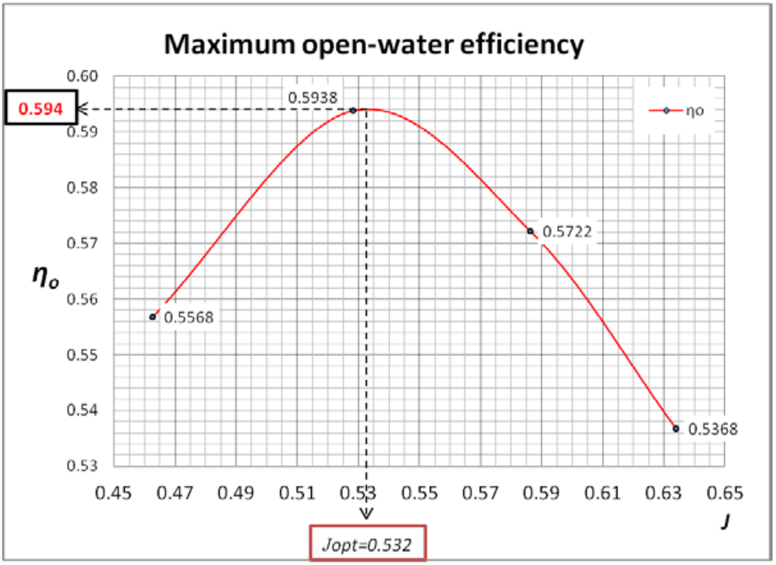


Preliminary design

$$\frac{K_Q}{J^5} = \frac{P_D \cdot n^2}{2\pi \cdot \rho \cdot V_A^5}$$



	J1	J2	J3	J4
P/D	0.6	0.8	1.0	1.2
J=	0.4625	0.5282	0.5863	0.6340
KT	0.0893	0.1586	0.2307	0.3037
KQ	0.0118	0.0224	0.0376	0.0571
η_o=	0.5568	0.5938	0.5722	0.5368



$$J = \frac{V_A}{n \cdot D}$$

D_{OPT}=5.21 m.

P/D_{OPT}=0.81

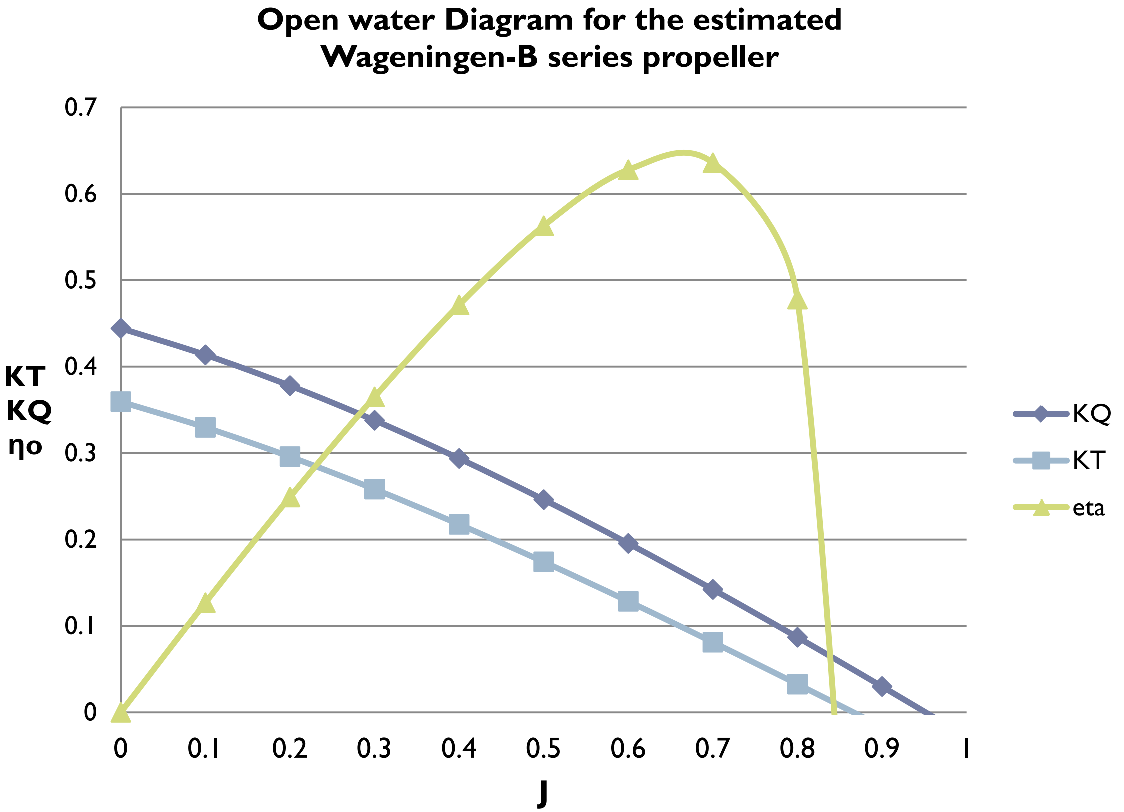
Preliminary design

Polynomials forms of K_T and K_Q

$$K_Q = \sum_{n=1}^{47} Cn\,(J)^{Sn}\,(P/D)^{t_n}\,(A_E/A_o)^{u_n}\,(Z)^{v_n}$$

$$K_T = \sum_{n=1}^{39} C_n\,(J)^{S_n}\,(P/D)^{t_n}\,(A_E/A_o)^{u_n}\,(Z)^{v_n}$$

$$\eta_0 = \frac{K_T}{K_Q} \cdot \frac{J}{2\pi}$$

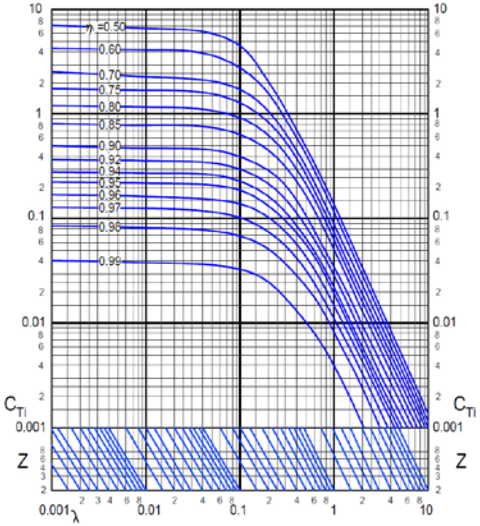

Open water Diagram for the estimated Wageningen-B series propeller

Detail design stage: Lifting-line theory

Data:
V_S, Z, D, n, A_E/**Ao,** T

$C_{TL}(1)$: Thrust loading coeff
λ : Advance ratio
$C_{TLi}(0)$: ideal thrust load. coeff.

KRAMER DIAGRAM



ηi (k):
ideal efficiency

Hydrodynamic Pitch angles :
-tan β
-optimum ***tan βI***
-Tip unloading factor ***tan βI x tuf***
$C_{TLi}(1)$
C_P :Power coefficient
P_D : Delivered Power

Design of Blade section:
$C_L(c/D)$
t/D
f/c

Lifting surface corrections:
f/c , P/D

Final blade geometry:
P/D, c/D, t/D, f/c

T	=595.68	[kN]
Q	=442.14	[kN-m]
C_T	= 0.70	Thrust coefficient
AE/Ao	=0.7	

Hydrodynamic in 2D

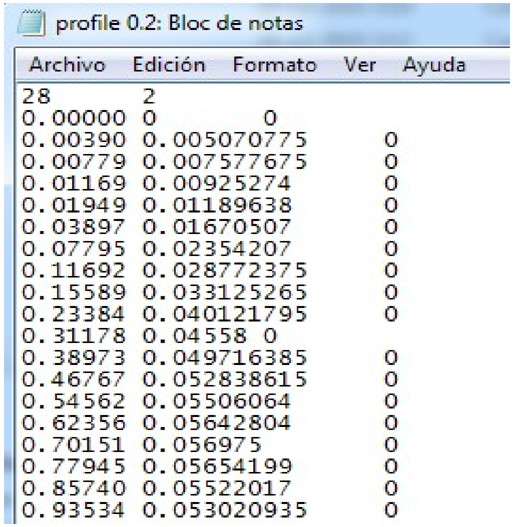
NACA-66(modified)

	Distribution	
chord	Camber	thickness
x/c	$y_c/fmax$	y/t_{max}
0	0	0
0.0025	0.0235	0.0445
0.005	0.0423	0.0665
0.0075	0.0595	0.0812
0.0125	0.0907	0.1044
0.025	0.1586	0.1466
0.05	0.2715	0.2066
0.075	0.3657	0.2525
0.1	0.4482	0.2907
0.15	0.5869	0.3521
0.2	0.6993	0.4
0.25	0.7905	0.4363
0.3	0.8635	0.4637
0.35	0.9202	0.4832
0.4	0.9615	0.4952
0.45	0.9881	0.5
0.5	1	0.4962
0.55	0.9971	0.4846
0.6	0.9786	0.4653
0.65	0.9434	0.4383
0.7	0.8892	0.4035
0.75	0.8121	0.3612
0.8	0.7027	0.311
0.85	0.5425	0.2532
0.9	0.3586	0.1877
0.95	0.1713	0.1143
0.975	0.0823	0.0748
1	0	0.0333

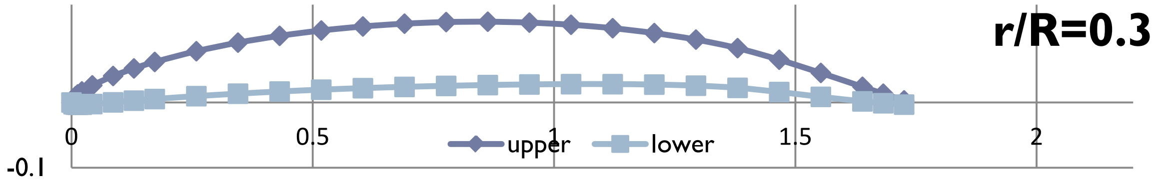
+

From lifting-line

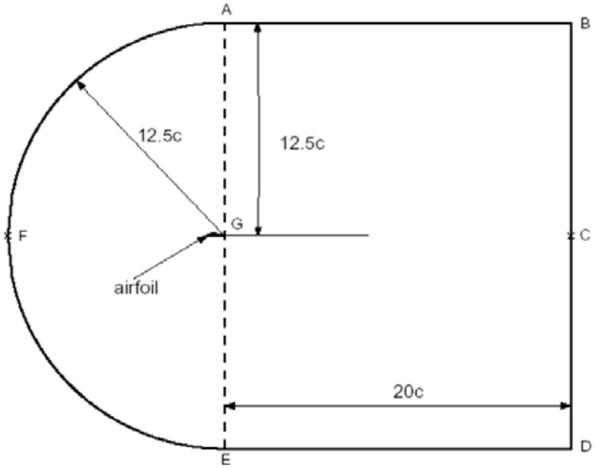
Final blade geometry:
P/D, c/D, t/D, f/c

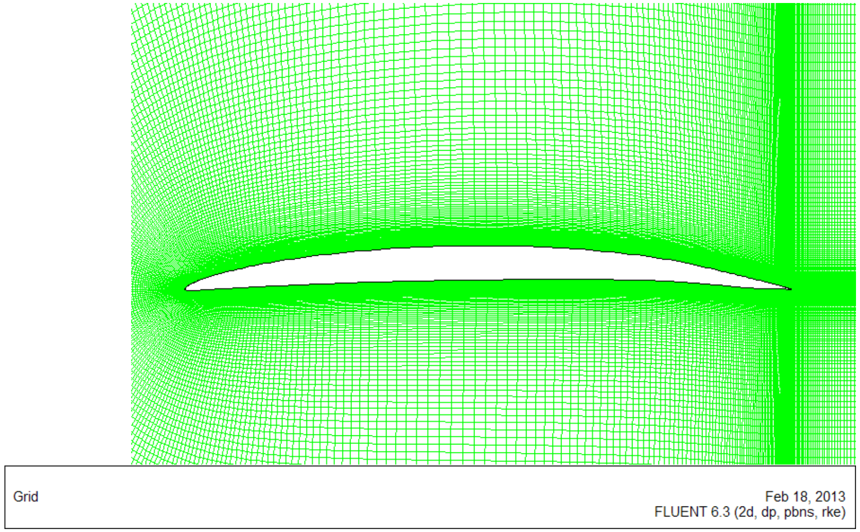


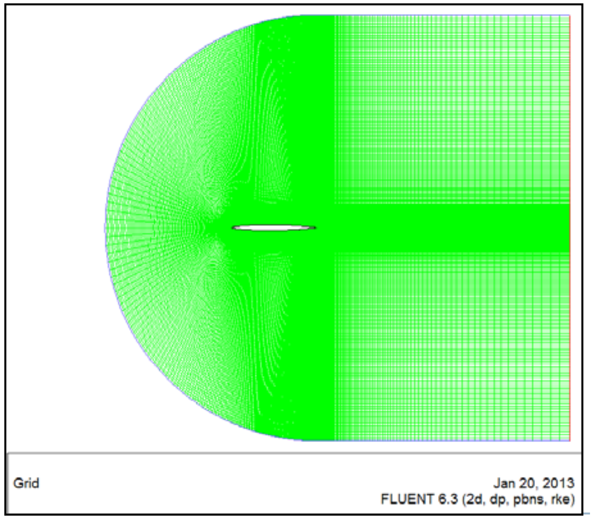
```
28         2
0.00000 0         0
0.00390 0.005070775      0
0.00779 0.007577675      0
0.01169 0.00925274       0
0.01949 0.01189638       0
0.03897 0.01670507       0
0.07795 0.02354207       0
0.11692 0.028772375      0
0.15589 0.033125265      0
0.23384 0.040121795      0
0.31178 0.04558 0
0.38973 0.049716385      0
0.46767 0.052838615      0
0.54562 0.05506064       0
0.62356 0.05642804       0
0.70151 0.056975         0
0.77945 0.05654199       0
0.85740 0.05522017       0
0.93534 0.053020935      0
```



Analysis of the design in 2D







Number of cells > 80000.

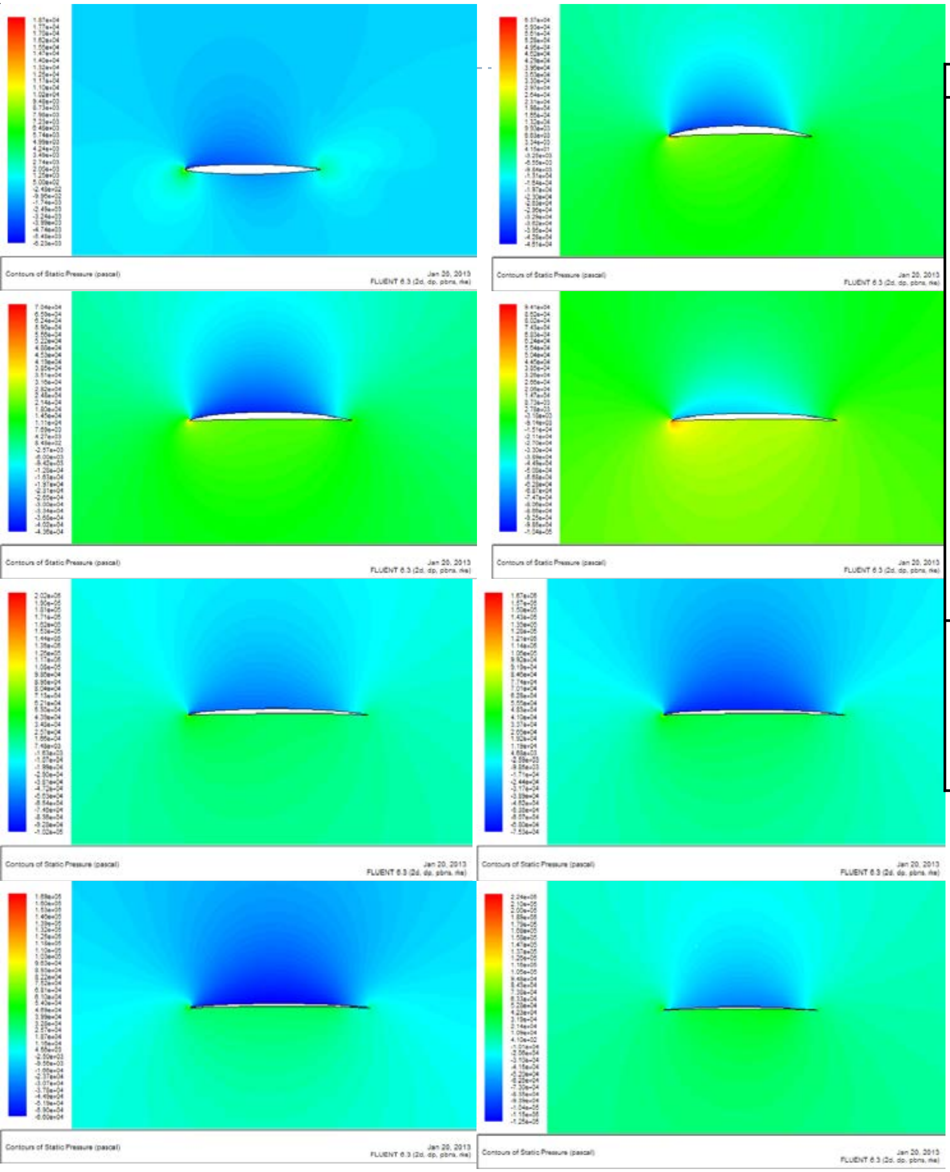
For small α the C_L is the same for

Spalart-Allamas

k-epsilon Realizable

k-omega SST

Hydrodynamic analysis in 2D



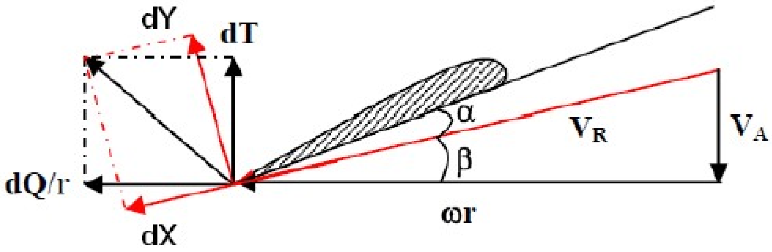
r/R	FLUENT 2D		β				
	C_L	C_D	rad	C_T	dT	SF	SFxdT
0.2	0.0586	0.0051	0.828	0.035828962	0.86	1	0.863107825
0.3	0.3573	0.0030	0.6329	0.286476365	28.86	4	115.4459527
0.4	0.2494	0.0028	0.5197	0.215100971	41.82	2	83.63990263
0.5	0.2355	0.0028	0.432	0.212646467	69.70	4	278.803107
0.6	0.1868	0.0028	0.3808	0.172367773	86.40	2	172.8075881
0.7	0.1462	0.0027	0.341	0.136907323	95.95	4	383.7882071
0.8	0.1085	0.0023	0.307	0.102773591	91.40	2	182.8091551
0.9	0.0793	0.0025	0.277	0.075604515	73.70	4	294.8027547
1	0	0	0.252	0		1	0

$$dT = \frac{1}{2}\rho \cdot c \cdot V_R \cdot (C_L \cos\beta - C_D \sin\beta)dr$$

Σ 1512.959775

∫ 131.3753405

Total Thrust = x4= **525.501[kN]**



Hydrodynamic analysis in 2D

r/R	FLUENT 2D		**β**			
	C_L	C_D	rad	C_Q	***dQ***	SFxdQ
0.2	0.0586	0.0051	0.8286	0.0466	0.5851	0.5851
0.3	0.3573	0.0030	0.6320	0.2135	16.8113	67.2454
0.4	0.2494	0.0028	0.5193	0.1262	25.5568	51.1136
0.5	0.2355	0.0028	0.4321	0.1011	43.1750	172.7000
0.6	0.1868	0.0028	0.3804	0.0719	56.3516	112.7032
0.7	0.1462	0.0027	0.3412	0.0515	65.7829	263.1316
0.8	0.1085	0.0023	0.3072	0.0350	64.8391	129.6782
0.9	0.0793	0.0025	0.2775	0.0241	55.0587	220.2347
1	0	0	0.2524	0	0	0
					Σ	1017.392
					∫	88.344
			Total Torque Q			x4=**353.374 [kN-m]**

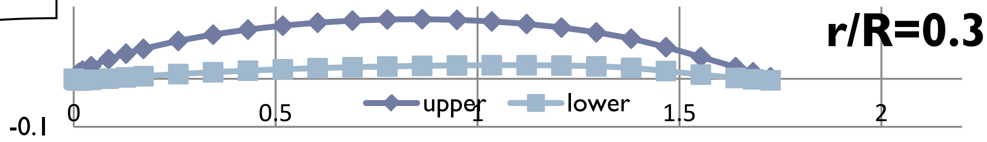
$$dQ = \frac{1}{2}\rho \cdot c \cdot V_R \cdot (C_L \sin\beta + C_D \cos\beta) r dr$$

	Lift-line	2D	%
T	=595.68	**525.5**	11.78%
Q	=442.14	**353.37**	20.0%

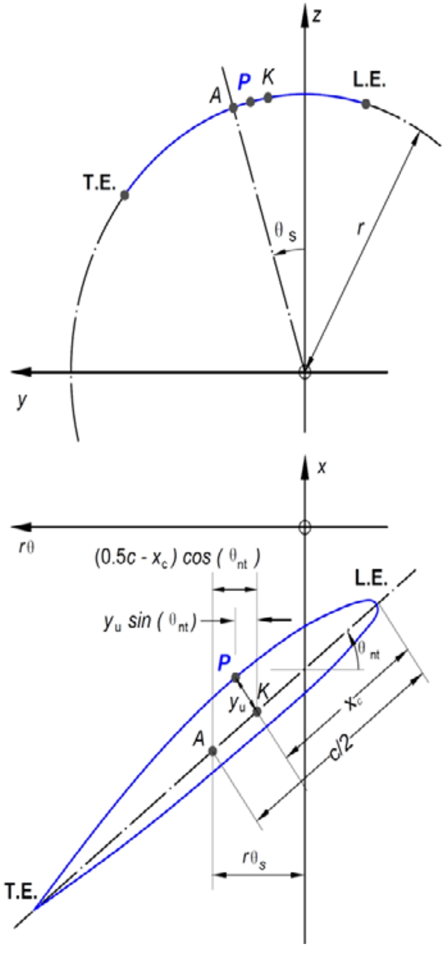
Hydrodynamic analysis in 3D

NACA-66(modified)

Final blade geometry:
P/D, c/D, t/D, f/c



r/R=0.3



$$\begin{bmatrix} X_p \\ Y_p \\ Z_p \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & -\sin\phi \\ 0 & \cos\phi & \cos\phi \end{bmatrix} \begin{bmatrix} x_p \\ y_p \\ z_p \end{bmatrix}$$

Marine Propellers and Propulsion, Carlton 2007

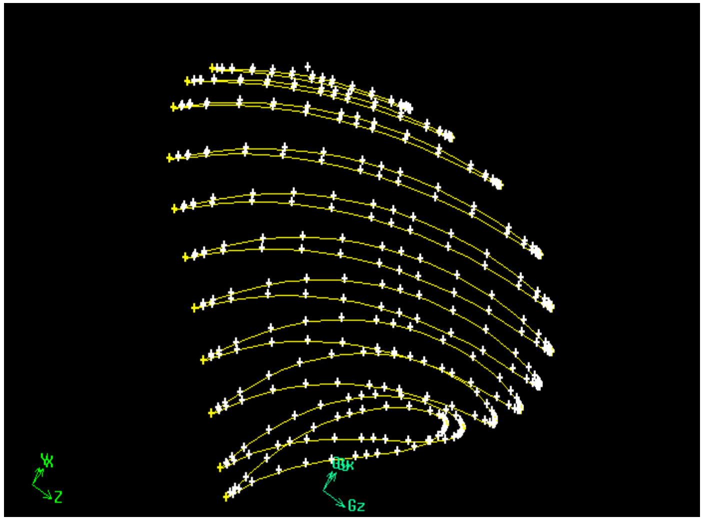
$$x_p = -[i_G + r\theta_s \tan(\theta_{nt})] + (0.5c - x_c)\sin(\theta_{nt}) + y_{u,L} \cos(\theta_{nt})$$

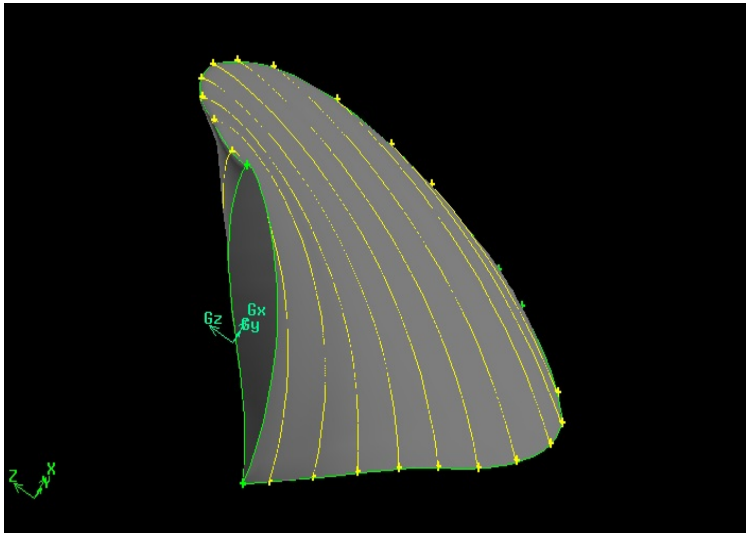
$$y_p = r \sin\left[\theta_s - \frac{180[(0.5c - x_c)\cos(\theta_{nt}) - y_{u,L}\sin(\theta_{nt})]}{\pi r}\right]$$

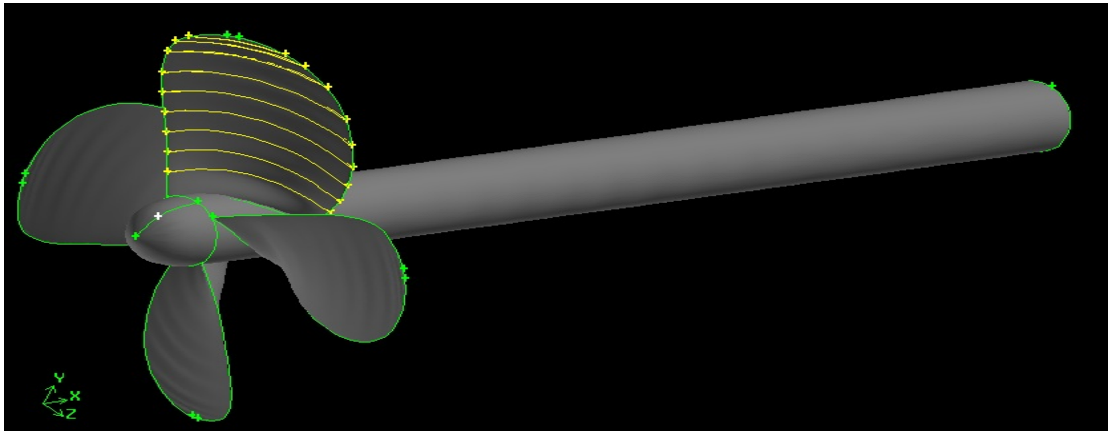
$$z_p = r \cos\left[\theta_s - \frac{180[(0.5c - x_c)\cos(\theta_{nt}) - y_{u,L}\sin(\theta_{nt})]}{\pi r}\right]$$

Hydrodynamic analysis in 3D

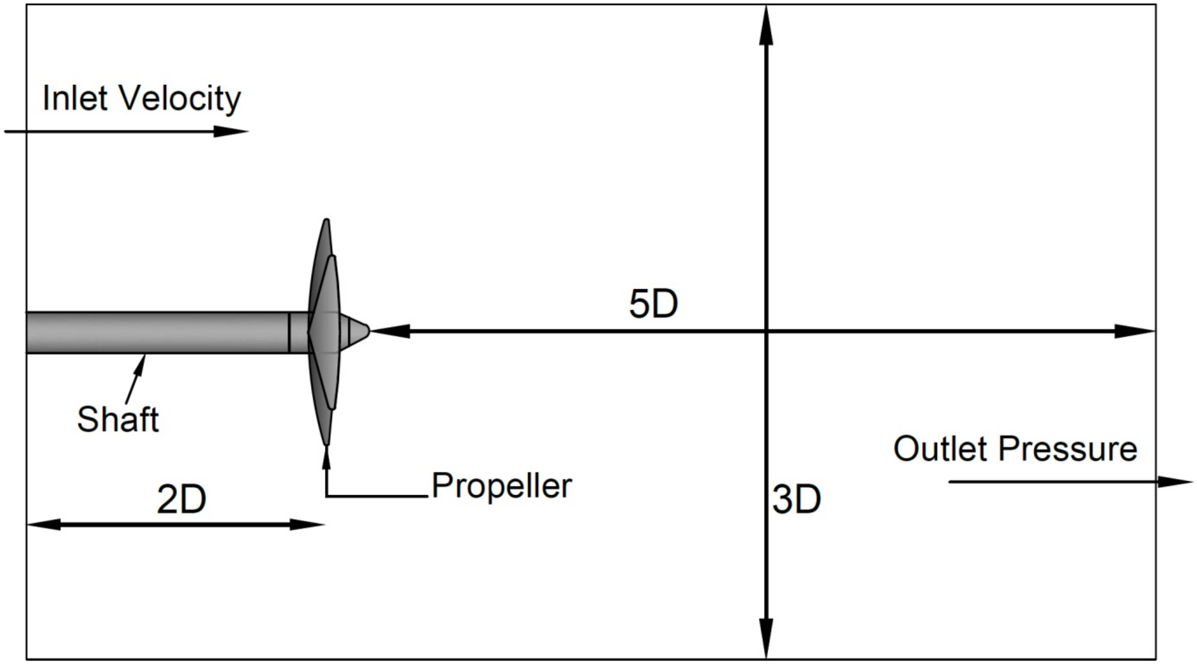
Preprocessing in Gambit







Hydrodynamic analysis in 3D
Preprocessing in Gambit



Moving Reference Frame

129 R.P.M.

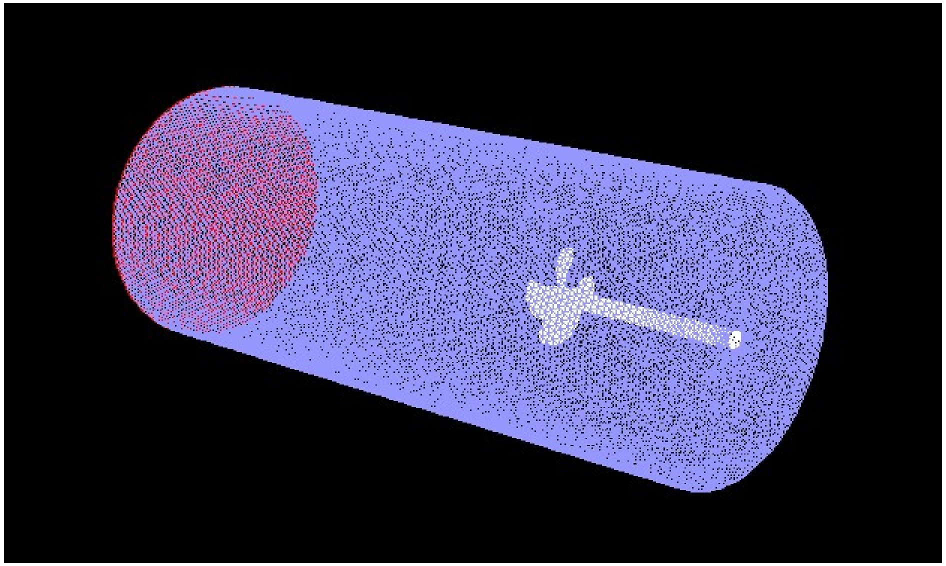
pressure-velocity method :SIMPLE

k-epsilon Realizable with standard Wall Functions

Second Order for Pressure

Second Order Upwind for
the Momentum,
Turbulent Kinetic Energy
Turbulent Dissipation Rate

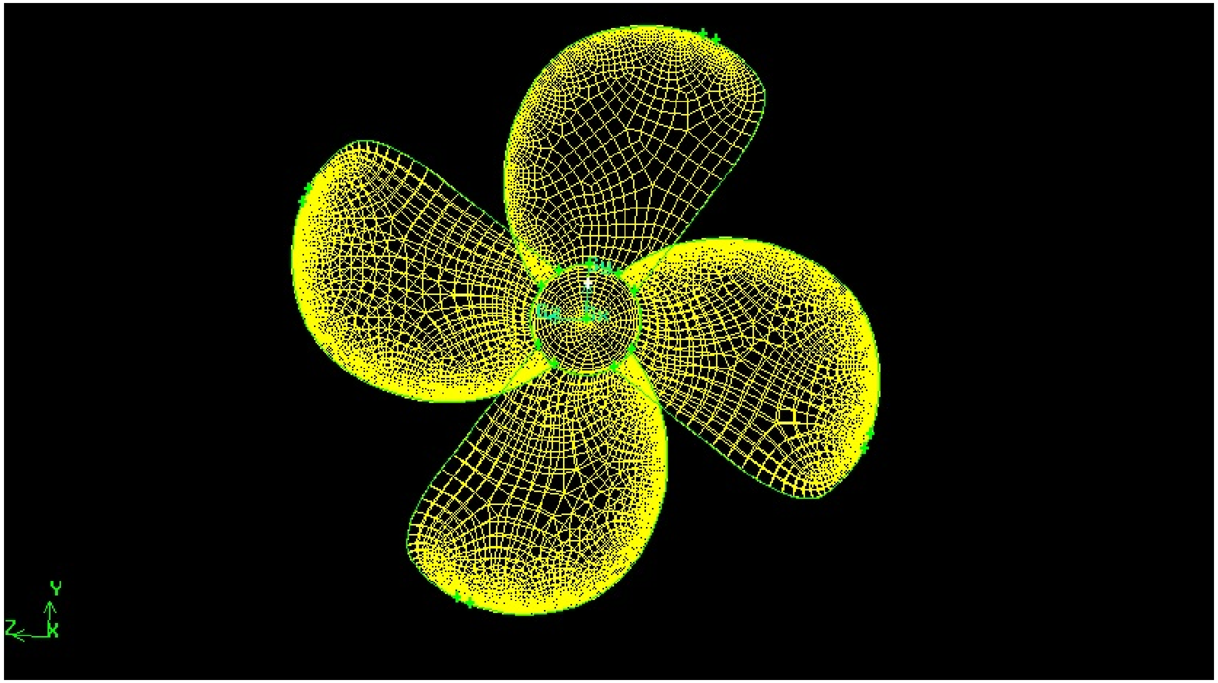
Hydrodynamic analysis in 3D
Preprocessing in Gambit



1.559.103 tetrahedral elements or Cells   182 Mb.

Angle	:20°	of the tetrahedral element
Growth rate	:1.2	
Max. size	:300	maximum size of the element in mm
Min. size	:10	minimum size of the element in mm

Hydrodynamic analysis in 3D
Preprocessing in Gambit

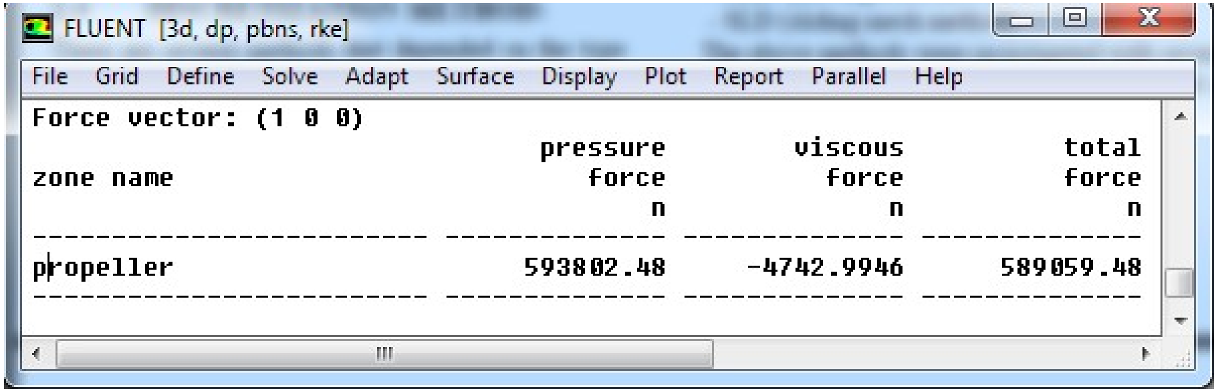


By using size function in Gambit

Hydrodynamic analysis in 3D

Analysis in Fluent 6.3

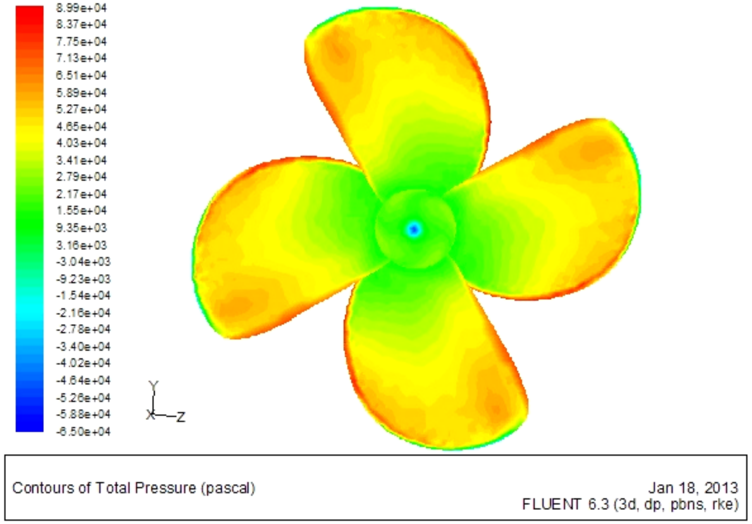
Vs = 17.4 Knots, = 8.95 [m/s]
V_A = 6.14 [m/s]
RPM = 129



```
Force vector: (1 0 0)
                                            pressure           viscous             total
zone name                                      force             force             force
                                                   n                 n                 n
-------------------------- ---------------- ----------------- -----------------
propeller                                  593802.48        -4742.9946         589059.48
-------------------------- ---------------- ----------------- -----------------
```

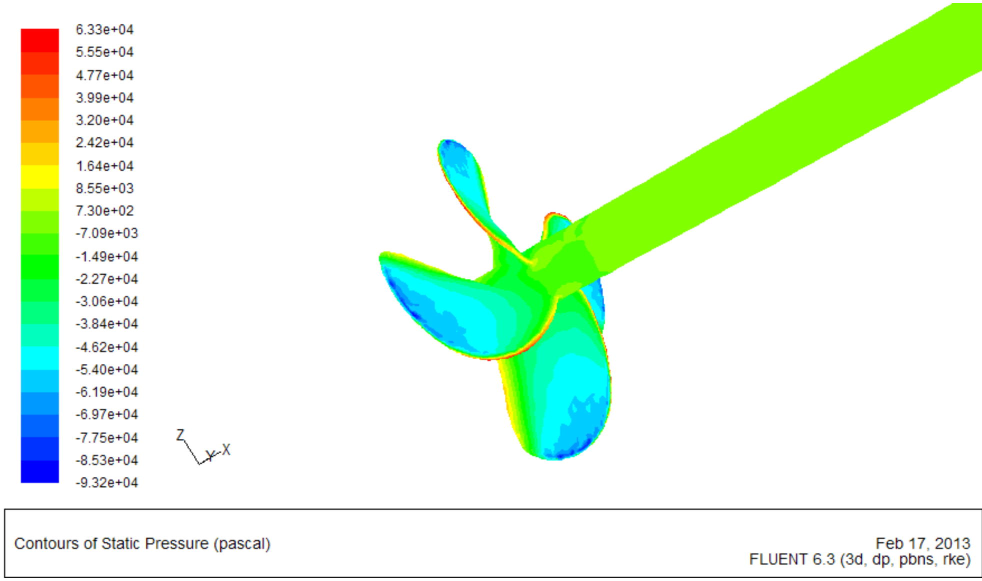
	Lifting-line	**RANS**	difference	difference
	kN	kN	kN	%
T =	595.68	589.06	6.62	1.11% less than **Lifting-line**
Q =	442.14	417.4	24.74	5.6 % less than **Lifting-line**

Hydrodynamic analysis in 3D
Post Processing in Fluent



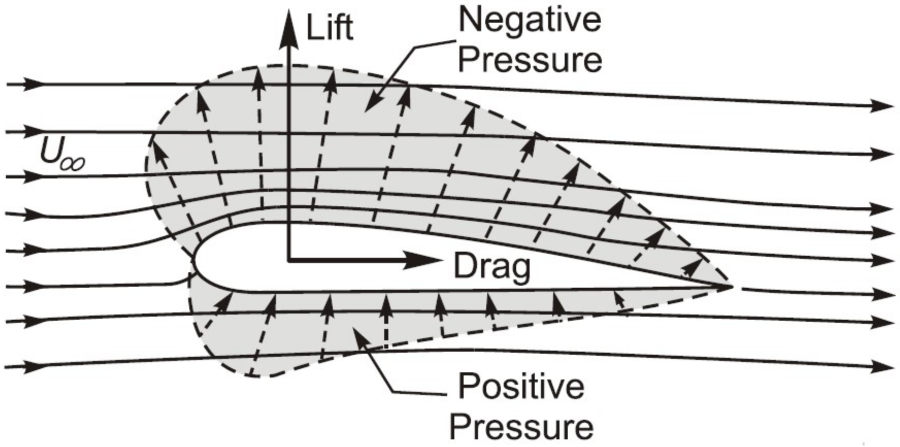
Contours of Total Pressure (pascal)

Jan 18, 2013
FLUENT 6.3 (3d, dp, pbns, rke)

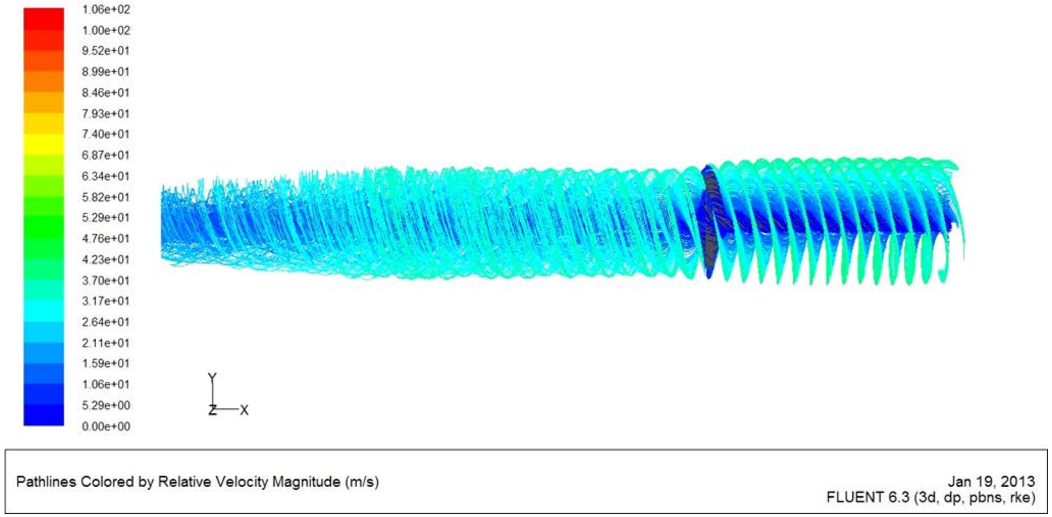


Contours of Static Pressure (pascal)

Feb 17, 2013
FLUENT 6.3 (3d, dp, pbns, rke)



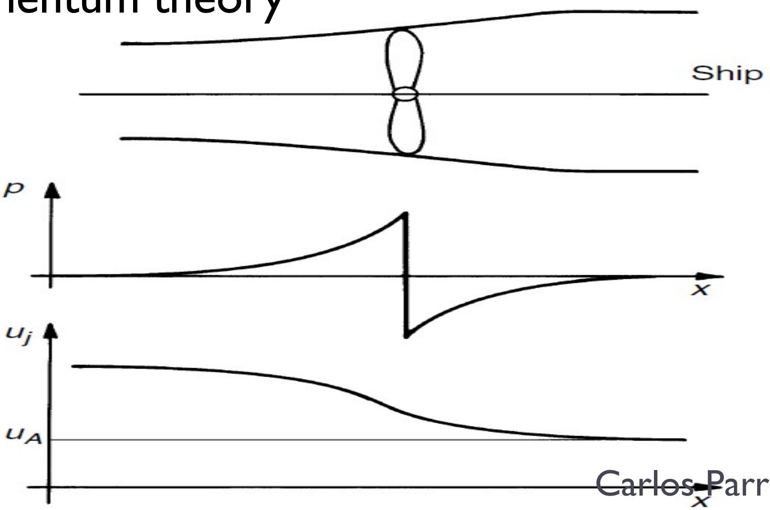
Hydrodynamic analysis in 3D
Post Processing in Fluent



Pathlines Colored by Relative Velocity Magnitude (m/s)

Jan 19, 2013
FLUENT 6.3 (3d, dp, pbns, rke)

Representation of the momentum theory



Results: Open water characteristics

Develope of the K_T, K_Q and η_o Diagrams

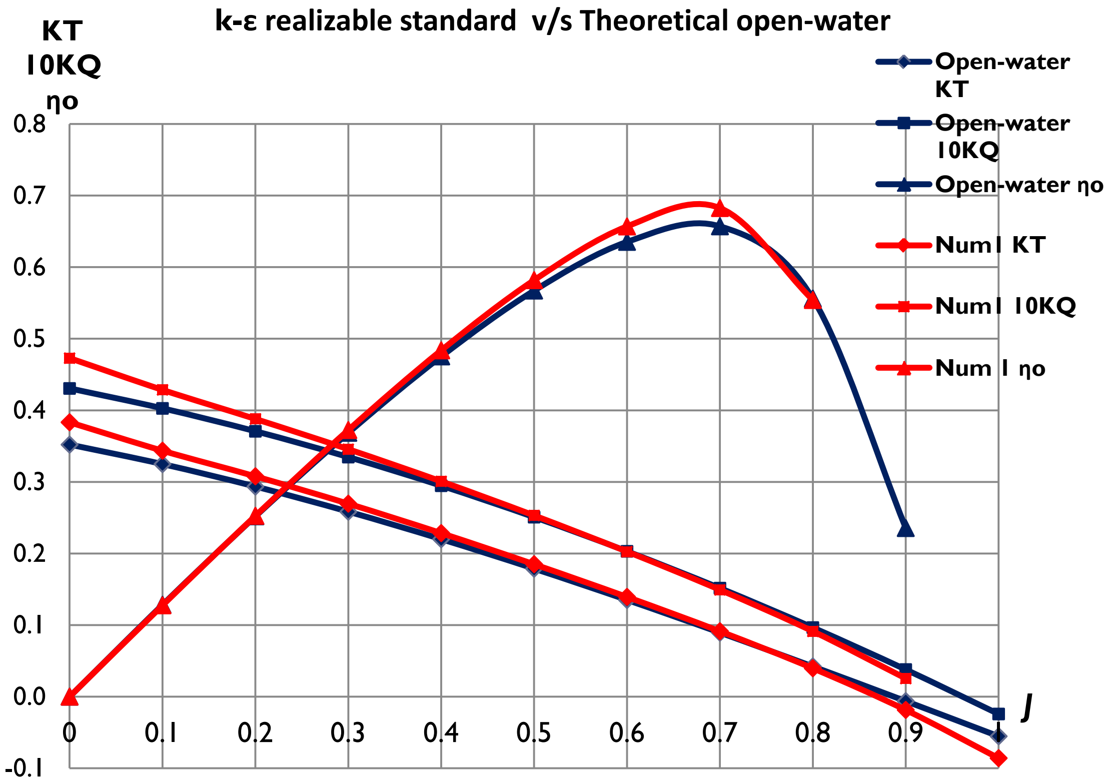
k-e realizable estándar

J	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
Va[m/s]	0	1.120	2.240	3.360	4.480	5.600	6.720	7.841	8.961	10.081	11.201
T[kN]	1337.99	1199.52	1074.58	941.1	797.53	645.73	486.41	318.97	138.55	-64.68	-299.9
Q[kN-m]	860.08	779.36	705.46	628.59	546.82	460.15	368.41	271.25	165.87	45.97	93.69
KT	0.3833	0.3436	0.3078	0.2696	0.2285	0.1850	0.1393	0.0914	0.0397	-0.0185	-0.0859
10KQ	0.4729	0.4285	0.3879	0.3456	0.3006	0.2530	0.2026	0.1491	0.0912	0.0253	0.0515
ηo	0	0.1276	0.2526	0.3724	0.4837	0.5818	0.6569	0.6826	0.5541	-1.0500	-2.6542

Wageningen Open water

J	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
K_{to}	0.3520	0.3248	0.2935	0.2584	0.2200	0.1787	0.1351	0.0894	0.0422	-0.0062	-0.0553
$10K_{Qo}$	0.4306	0.4027	0.3707	0.3347	0.2946	0.2507	0.2030	0.1516	0.0965	0.0379	-0.0242
η_o	**0.0000**	**0.1284**	**0.2520**	**0.3686**	**0.4753**	**0.5673**	**0.6353**	**0.6570**	**0.5561**	**0.2355**	**3.6378**

Results: Open water characteristics



optimum ***Jopt***=0.53

For the same $A_{E/}Ao=0.7$ and P/D=0.81

Conclusions

Lifting-line increases Coefficients K_T, K_Q and η_o obtained from W-B series, increasing, A_E/Ao as well.

Good prediction for THRUST using k-epsilon Realizable turbulence model.

The TORQUE result was not so reliable.

The engine with P_B=6900 kW would give the desired Thrust for V_S=17.4 kn

It is very important to achieve good results starting with open water analysis or steady flow analysis, because in the end the final aim is to achieve good results in unsteady flows