The design of a bulk carrier propulsion system

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Galati, February 2014

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ABSTRACT

The design of a bulk carrier propulsion system

By **Ibrahim Manaure Trujillo**

Competitive ships must be designed to survive challenges of a globalized market, increase of speed, increase of cargo capacity, minimum fuel consumption and maximizing maneuverability are among them, in consequence, lots of efforts are being placed to overcome mentioned ideas. Regarding propulsion systems, our aim is to develop designs to give maximum propulsive efficiency without noise and vibration.

The objective of this master thesis is to design a bulk carrier propulsion system; fundamental of the design is the selection and integration of the main components (prime mover, transmission and propulsor) into a functional system. For the propulsion system of the ship it was decided to use a low speed diesel engine with directly driven fixed pitch propeller.

As stated before, propulsion systems consist of three components, engine, transmission, and propeller. Engine will be selected by its power (MCR) to overcome ship resistance accounting for losses, shaft line will be design using GL rules for its dimensioning, and propeller development will be divided in three stages, preliminary design, detailed design and analysis.

Determination of the required propulsion power and engine sizing requires previous knowledge of the quasi-propulsive coefficient. At initial point, propeller diameter was estimated by considering ship draught in ballast condition, to avoid air drawing; Wageningen B Series data was used to obtain optimum propeller velocity of rotation *rpm* for maximum open water efficiency; once engine brake power was obtained, selection of engine was performed.

Because main engine influences the propeller through the propeller rpm and delivered power, new propeller diameter for maximum efficiency was computed satisfying required clearance; also, propeller was designed to absorb a given delivered power (15% sea margin and 10 % engine margin taken into consideration). Main results of this stage are diameter D, number of blades z, expanded area ratio and propeller mean pitch ratio P/D.

Second stage in propeller design procedure is to find the blade geometry for a specified distribution of blade loading over the radius. To achieve this goal, a wake adapted propeller was designed using an in-house code for lifting line theory with lifting surface corrections.

Finally, propeller geometry was used as input data to start the third and last stage of propeller design, called analysis, where we perform numerical analysis of the open water characteristics and hydrodynamic performances of the wake adapted propeller. Primordial objective of this stage are the calculation of open water characteristics, calculations of pressure distribution on propeller blades and calculation of the unsteady forces and moments acting on propeller shaft. If satisfactory results are obtained at this stage, the design of the propeller is concluded, if not, an iterative design cycle will take place with a changed propeller geometry.

LIST OF SYMBOLS

∇	ship's displacement (m^3)
L_{OA}	overall length of the ship (m)
L_{WL}	length of the waterline (m)
L_{PP}	length between perpendiculars (m)
B_{WL}	breadth at waterline (m)
A_m	midship section area (m^2)
A_{WL}	waterline area (m^2)
C_B	block coefficient
C_M	midship section coefficient
C_P	longitudinal prismatic coefficient
C_{WL}	waterplane area coefficient
lcb	longitudinal center of buoyancy (m)
R_T	total resistance
R_F	frictional resistance
R_R	residual resistance
C_F	frictional resistance coefficient
P_E	effective (towing) power (kW)
P_T	thrust power delivered by the propeller to water (kW)
P_D	delivered power (kW)
P_B	brake power (kW)
V	ship's speed (m/s)
V_A	speed of advance (m/s)
T	thrust force

w	wake fraction coefficient
t	thrust deduction coefficient
n_H	hull efficiency
n_R	relative rotative efficiency
n_O	open water propeller efficiency
n_B	behind hull propeller efficiency
n_D	propulsive efficiency
n_S	shaft efficiency
J	advance number of the propeller
Q_B	engine shaft torque $(kN.m)$
n	revolutions per second (s^{-1})
D	propeller diameter (m)
Z	number of propeller blades
EAR	expanded blade area ratio
p	propeller pitch
K_T	thrust coefficient
Q	propeller force
K_Q	torque coefficient
S_A	apparent slip ratio
S_R	real slip ratio
SMCR	specified maximum continuous rating

1. INTRODUCTION

Large vessels require large amount of power, which means large fuel consumption. Great efforts are being placed to build ships with the minimum required installed power. New design concepts and technologies are aimed at cutting operating cost. Energy saving devices, reducing the lightweight construction, and optimizing main dimensions are among the list, but all of these hard wok falls apart if the main energy consumer is not efficiently design, the propulsor.

This thesis presents a step by step design of a 32,000 metric tonnes bulk carrier propulsion system, from the selection of engine and design of propeller, to the design of the shaftline.

Propulsion system will consist of a fixed pitched propeller directly coupled to a low speed diesel engine. Special importance will be placed to the design of the propeller, because it represents an important component of the propulsion system. Design will be divided in three stages: preliminary design, detailed design and hydrodynamic analysis of the final propeller.

On the first stage, main characteristics of propeller such as diameter, rotation rate, blade area ratio will be obtained using B Wageningnen series data. Attention will be driven to the avoidance of cavitation while operating at maximum efficiency.

Secondly, detailed design will be performed via lifting line theory. The objective of this stage is to find the propeller geometry for a radially varying distribution of the loading.

Using CFD methods, final propeller will be investigated in steady conditions, in uniform flow, and in a radially varying inlet velocity, simulating the ship wake to compare the results with lifting line theory. Also, comparisons of results for open water characteristics between two different CFD codes, Shipflow and Fluent, will be established.

Finally, connecting the engine with the propeller is the transmission. Design will be according to classification society rules. 3D geometry of the shaft with locations for bearings is expected. Checking of the shaftline mechanical behavior is out of the scope of the thesis.

2. OBJECTIVES

2.1 Main Objective

The objective of this master thesis is to design a bulk carrier propulsion system; fundamental of the design is the selection and integration of the main components (prime mover, transmission and propulsor) into a functional system.

2.2 Specific Objectives

- Propulsive power estimation.
- Selection of engine.
- Preliminary design of the propeller using methodical series data.
- Final design of the propeller using lifting line theory.
- CFD analysis of global propeller performance in open water and in a radially varying inflow flow.
- Design of the shaftline according to classification society's rules.
- Creation of shaftline drawings and assembly.

3. CASE OF STUDY

3.1 Ship general description and design speed

The vessel is a 32,000 metric tonnes deadweight ocean going bulk carrier with bulbous bow, transom stern, flush decker with raised forecastle and poop deck, open water type stern frame, single rudder and single screw propeller.

The propulsion machinery and all living quarters including navigation bridge are located at the aft part of the ship.

Table 1. Ship main dimensions and block coefficient

Length, overall (Abt.)	182.50 m
Length, between perpendiculars	175.00 m
Breadth, moulded	29.00 m
Depth, moulded	14.75 m
Design draught, moulded	9.85 m
Scanting draught, moulded	10.20 m
Block coefficient	0.806

Selection of the design speed will be based on normal service speed for bulk carriers. Figure 1 below presents typical values for service speed according the type of vessel.

Ship type	Block coefficient $C_{B, PP}$	Approximate ship speed V in knots
Lighter	0.90	5 – 10
Bulk carrier	0.80 – 0.85	12 – 16
Tanker	0.80 – 0.85	12 – 17
General cargo	0.55 – 0.75	13 – 22
Container ship	0.50 – 0.70	14 – 26
Ferry boat	0.50 – 0.70	15 – 26

Figure 1. Examples of block coefficients and speed for different type of vessels. Taken from Man Basic Principles of Ship Propulsion

Following recommendations and experience from other vessels, the propulsion system will be design for the service speed at design draught to be about 14 knots.

3.2 Ship resistance

Total resistance is the force exerted by the water in opposition to the movement of the ship; on calm water is composed by different components [7]:

- Frictional resistance
- Wave making resistance
- Eddy resistance
- Air resistance

Correct calculation of ship resistance is of vital importance because it affects engine sizing directly. The latter must develop sufficient power to rotate the propeller in order to generate a required thrust to overcome the resistance. Various methods have been developed to solve the problem:

- Traditional and standard series method

- Regression based methods
- Direct model test
- Computational Fluid Dynamics

Nowadays, regression based methods and direct model test are the most used to obtain ship resistance. The first one, uses empirical equations developed from experimental studies of numerous vessels, this gives a sensibly good first estimation of the resistance. For a preliminary design stage, regression based methods provide a reliable solution. An example of such method can be found in reference [10].

Secondly, direct model test rely on the experimental approach to obtain the ship resistance. A scale model of the ship is constructed and a resistance test is performed on a towing tank.

In our case, ICEPRONAV Engineering performed resistance model test of the bare hull. Results are plotted on figure 2.

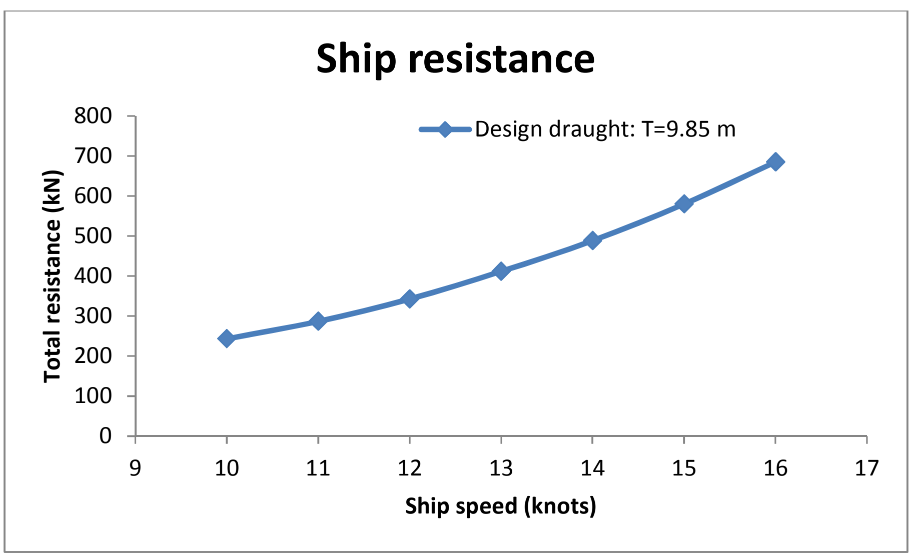


Figure 2. Resistance test results

Exact values of resistance are hidden due to confidential matters.

3.3 Type of propeller

Basically there are two types of marine propellers, fixed pitch propellers and controllable pitch propellers.

Controllable pitch propeller includes in the hub a mechanical or hydraulic system that rotates the blade around it vertical axis in order to control the propeller pitch in different service conditions. This type of propeller gives highest propulsive efficiency over a wide range of rpm, for different ship speeds and loaf conditions by automatic pitch adjustment.

On the other hand, fixed pitch propeller are made from single castle, they are often design to be efficient at one speed therefore ideal for long voyages at constant speed.

Selection between a controllable pitch propeller and a fixed pitch propeller results from a number of considerations. According to Carlton [5], these are:

- Role of vessel
- Special requirements
- Initial installation costs
- Running costs
- Maintenance requirements
- Service availability
- Legislative requirements

Because of the scope of present work, we will discuss only about the two primary requirements. On the first place, bulk carriers are meant to sail only at one design speed and maneuverability is not critical in comparison to offshore and tugs market.

For vessels where speeds changes and course changes do not occur often, controllable pitch propellers will be a complex solution. Fixed pitch propeller present a reliable solution due to simple operation and they deliver maximum efficiency at one operating point (ship speed) if designed correctly.

Reasoning with the above, a fixed pitch propeller will be used for the design of the propeller.

4. PROSULSIVE POWER ESTIMATION AND SELECTION OF ENGINE

4.1 Hull-propeller interaction coefficients

The flow entering propeller plane is affected by the ship hull shape. There exist two main factors that take into account these effects, the wake and the trust deduction factor. The first is to consider that the propeller inflow is slower than the ship speed, and the later to allow for the increased thrust in a propulsion test in comparison to a resistance test.

As we have no information for the wake and thrust deduction coefficients, we must estimate them using empirical correlations given by the expressions [1]:

For the mean wake (Troost for cargo ships):

$$w = 0.25 + 2.5 * (C_b - 0.6)^2$$

$$w = 0.3563$$

For the thrust deduction coefficient (Danckwardt for cargo ships):

$$t = 0.5C_b - 0.15$$

$$t = 0.2531$$

4.2 Preliminary open water efficiency estimation

Our vessel is a bulk carrier type; important in this type of vessels is the ballast draught because they are often sailing at this condition. Differences between design and ballast draught are often so large that propeller immersion can be affected. To avoid this phenomenon, propeller diameter, at initial design stage, will be defined as:

$$D = 0.65 * draught_{ballast}$$

$$D = 0.65 * (8.4) = 5.46\ m$$

The thrust necessary to propel the ship at 14 knots is defined by the expression:

$$T = \frac{R}{1 - t}$$

$$T = 653.37\ kN$$

where R is the ship resistance at 14 knots.

Propeller must operate in a non cavitating regime, to achieve this, minimum blade area ratio will be defined according to Keller criterion:

$$EAR = K + \frac{(1.3 + 0.3 * Z) * T}{p_o - p_v + \rho * g * h} = 0.5263$$

Where K is equal to 0.2 for single screw vessels and h the propeller immersion depth in meters.

According to previous results, blade area ratio will be considered to be 0.55. Table 2 presents a summary of data available until now.

Table 2. Summary of input data

Va (m/s)	4.63
Propeller diameter (m)	5.46
Thrust (kN)	653.37
EAR	0.55

Next procedure will use Wageningnen B-series diagrams to obtain the velocity of rotation for maximum open water efficiency using as input data table above. The procedure to do so, is explained below:

Advance coefficient:

$$J = \frac{V_A}{n * D} \quad (1)$$

Thrust coefficient:

$$K_T = \frac{T}{\rho * n^2 * D^4} \quad (2)$$

Combining (1) and (2) to eliminate the unknown velocity of rotation we obtain:

$$K_{T,ship} = \frac{T}{\rho * V_A^2 * D^2} * J^2 \quad (3)$$

Equation 3 is called ship curve, as felt by the propeller. Varying value of J in steps of 0.05 a parabolic curve is obtained. Intersection of this curve with K_T curves from B-Wageningnen diagrams for a four bladed propeller with EAR 0.55 will give the corresponding advance coefficients for each pitch ratio. Soon after, torque coefficient is obtained.

A MATLAB application that computes B-Wageningen characteristics for any number of blades, any blade area ratio and all pitch ratios was developed during the course of the thesis (see Appendix section). This application relies on two polynomials for K_T and K_Q derived with multiple regression analysis as follows:

$$K_T = \sum_{s,t,u,v} C_{s,t,u,v}{}^{T} (J)^s \left(\frac{P}{D}\right)^t \left(\frac{A_E}{A_o}\right)^u (Z)^v \quad (4)$$

$$K_Q = \sum_{s,t,u,v} C_{s,t,u,v}{}^{Q} (J)^{s} \left(\frac{P}{D}\right)^{t} \left(\frac{A_E}{A_o}\right)^{u} (Z)^{v} \quad (5)$$

Terms to control in equations above are the advance ratio, P/D, A_E/A_o and number of blades. Other coefficients and terms are given in the Appendix section.

Results of combination of propeller curves and ship curve are shown in figure 3 below.

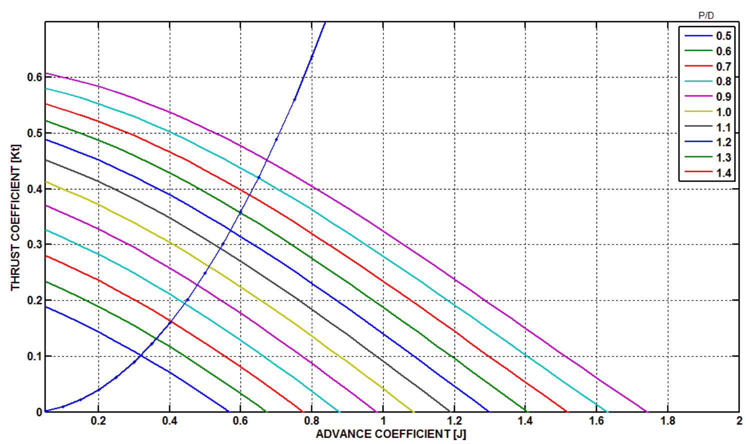


Figure 3. Intersection of K_T curves

Extracting values of intersection and computing torque coefficient, open water efficiency and velocity of rotation, table 3 can be constructed.

Table 3. Intersection points between curves with corresponding rotation rate

P/D	J	K_T	K_Q	η	n (rpm)
0.5	0.3189	0.10173	0.0112	0.46102	159.7
0.6	0.3626	0.1313	0.0151	0.50182	140.5
0.7	0.4039	0.1625	0.0201	0.51971	126.1
0.8	0.4422	0.1949	0.0261	0.52556	115.2
0.9	0.4779	0.2278	0.0332	0.52190	106.6
1	0.5115	0.2607	0.0412	0.51514	99.6
1.1	0.5428	0.2935	0.0501	0.50611	93.8
1.2	0.5717	0.3258	0.0599	0.49491	89.1
1.3	0.5994	0.3575	0.0702	0.48583	85.0
1.4	0.6247	0.3889	0.0811	0.47678	81.5

Maximum efficiency obtained is highlighted in yellow. Velocity of rotation for maximum efficiency is 115.2 rpm, with a value of $\eta = 0.52556$. For a graphical view of the results, figure 4 was created.

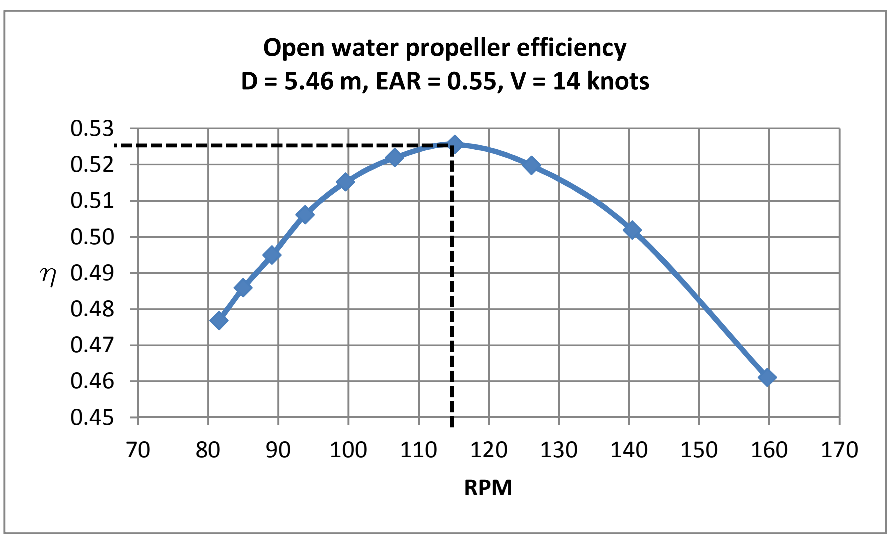


Figure 4. Efficiency vs propeller rotation rate

4.3 Brake power estimation

Determination of the required propulsion power and engine sizing requires working from a hull total tow rope resistance prediction to the required installed prime mover brake power [2].

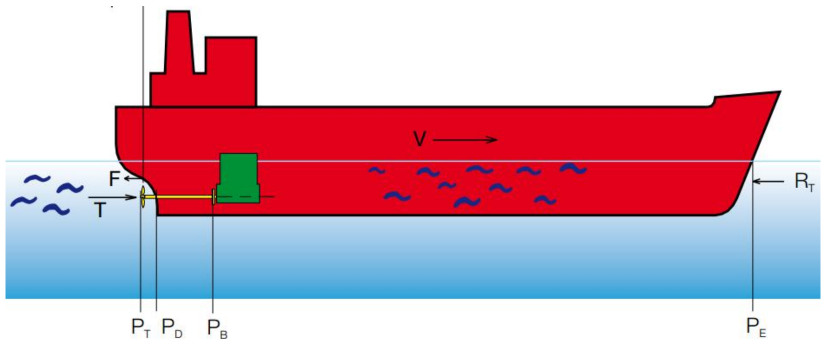


Figure 5. Propulsion of a ship

Relation between effective power and engine brake power is given as follows:

$$P_b = \frac{P_E}{\eta_h \eta_o \eta_r \eta_s \eta_b \eta_t} \quad (6)$$

Equation 6 presents all efficiencies related to the powering of the ship. In our case, propeller is directly coupled ($\eta_t = 1$), and according to guidance for sterntube and line bearing efficiencies $\eta_s \eta_b = 0.98$, relative propulsive efficiency and hull efficiency were obtain by using the formulas:

Hull efficiency:

$$\eta_h = \frac{1-t}{1-w} = \frac{1-0.2531}{1-0.3563} = 1.1603$$

Relative rotative efficiency:

$$\eta_r = 0.9922 - 0.05908 * EAR + 0.07424 * \left(C_p - 0.0225 * lcb\right) = 1.014$$

Once the information is completed we can build table 4 with all values for the vessel:

Table 4. Efficiencies for the vessel at 14 knots

η_h	1.1603
η_o	0.52556
η_r	1.014
η_s	0.98
η_b	1
η_t	1

Substituting in equation 6 we obtain:

$$P_B = \frac{3514.7}{(1.1603)(0.52556)(1.014)(0.98)(1)(1)} = 5799\ kW$$

Because of resistance was estimated for ideal conditions, we need to include power margins to overcome ship resistance on real operating condition. Two margins will be considered, sea margin, and engine margin. The first to take into account waves, wind, hull fouling etc, and the latest to operate the engine on an acceptable service point. Also a power take-off will be included for auxiliary power purposes.

Table 5. Power margins and total brake power of the engine

	Load
Sea margin	15%
Engine margin	10%
PTO	500 kW
TOTAL (kW)	**8005**

4.4 Selection of engine

Because there is a wide variety of prime movers: gas turbines, steam turbines, diesel engines, electric motors and even nuclear power plants, first question that arises our mind in the selection is which one to choose.

Preferred choice for merchant ship is the diesel engine. Main advantages are the relatively inexpensive fuel, low sensitivity to fuel quality and low maintenance. They are available in a variety of velocity of rotations, from low (< 250 rpm) to high speed (>1000 rpm).

Maximizing propeller efficiency is often associated with large diameters with low rotation rate. Taking this as a starting point, we will select a low speed diesel engine to avoid the necessity of a reduction gear.

It's important to know the power required per cylinder, considering six (6) cylinders for the engine to avoid any vibratory problems in operation with a four bladed propeller, doing so, we obtain:

$$\frac{power}{cyl} = \frac{8005\ kW}{6} = 1334\frac{kW}{cyl}$$

For the engine speed of rotation we will search for one that rotates as near as possible to n = 115.2 rpm, which is the speed for maximum efficiency for the propeller as stated in section 3.2.

From available catalogues on internet from principal manufactures, and with the two characteristics stated before, selected engine is presented below:

Table 6. Main characteristics of engine

Manufacturer	MAN B&W
Model	6S46MC-C8
Number of cylinders	6
kW/cyl	1380
Speed (rpm)	129
Engine power (kW)	8280

Power speed combinations of the engine are shown in the layout diagram in figure 6. L_1 indicates the nominal maximum continuous rating.

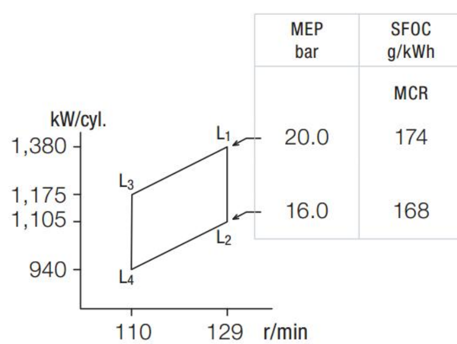


Figure 6. Engine curve. Taken from MAN Marine Engines catalogue 2010.

Any combination of speed and power inside the limits of the diagram are applicable.

5. PROPELLER DESIGN

5.1 General considerations

Propeller design can be divided in three stages: preliminary design, detailed design and analysis.

On the first stage, preliminary design, we use methodical series data based on open water test for model propellers to obtain characteristics for optimal efficiency. Among them, we find: diameter, number of blades, average pitch ratio and blade area ratio. At this stage, propeller is designed to attain average flow conditions behind the ship.

Subsequently, the second stage deals with the determination of necessary blade geometry to generate desired thrust or to consume a defined delivered power. Analytical methods are used to fulfil the task.

Finally, after the geometry of the propeller is completely defined, the propeller is analyzed in all operating conditions, steady and unsteady. The objective is to find the pressure distribution on propeller blades, evaluate the hydrodynamics performances of propeller in off design conditions and determine how the ship's wake influences the cavitation performances and the unsteady forces induced by the propeller transmitted to the ship throughout the hull and bearings.

5.2 Propeller design point

Propeller must be designed to consume totality of engine delivered power at a given rotation rate. Power delivered to the propeller is calculated as follows:

$$P_D = (0.9 * P_B - PTO) * 0.85 * \eta_s \quad (7)$$

$$P_D = 5791.016\ kW$$

In equation 7, 0.9 values corresponds to 0.10 engine margin (EM) because is not recommended to use the engine at the maximum continuous power MCR, and 0.85 corresponds to sea margin (SM), given by the difference between the power required in real sailing conditions (heavy seas, hull covered with algae) to the power on ideal conditions.

The engine speed of rotation is to be adjusted, because we will operate it in a derated condition. Figure below present a brief general explanation for the diminishing of the velocity of rotation for the calculation of the propeller.

$$n = n_o \sqrt[3]{\frac{100-EM}{100}} = 129 * \sqrt[3]{\frac{100-10}{100}} = 124.5\ rpm$$

where EM is the Engine Margin.

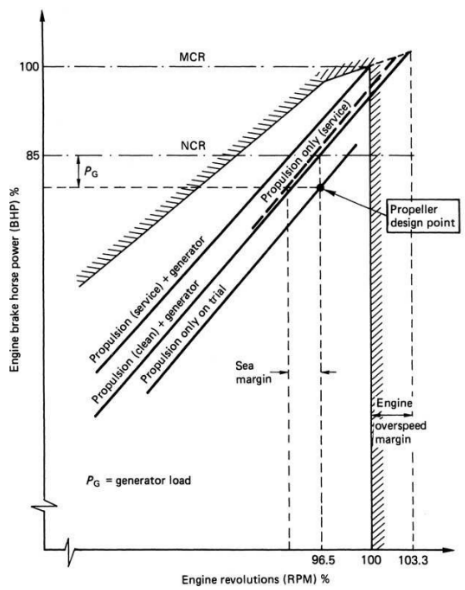


Figure 7. Representative engine curves with corresponding propeller design point. Taken from Carlton, Marine Propeller and propulsion, Part 22 Propeller design

Figure above shows a propeller design point inside the limits of a layout diagram of an engine. Notice that velocity of rotation is lower than a 100% due to the use of the engine at a NCR different of MCR.

5.3 Optimal propeller diameter

A new diameter that satisfies new velocity of rotation must be computed to obtain maximum efficiency, for this purpose a procedure similar to section 4.2 is shown below:

Torque coefficient:

$$K_Q = \frac{Q}{\rho * n^2 * D^5} \qquad (8)$$

Brake power:

$$P_B = 2 * \pi * n * Q \qquad (9)$$

Delivered power:

$$P_D = P_B * \eta_s * \eta_b * \eta_t \qquad (10)$$

Combining equations (8), (9), and (10) to eliminate the unknown diameter we obtain

$$K_Q = \frac{P_D * n^2 * J^5}{2\pi * \rho * V_A^5} \qquad (11)$$

Varying the value of J in steps of 0.05 a curve is obtained. Intersection of this curve with Kq curves from B-Wageningnen diagrams for a four bladed propeller with EAR 0.55 will give the corresponding advance coefficients for each pitch ratio. Soon after, thrust coefficient is obtained.

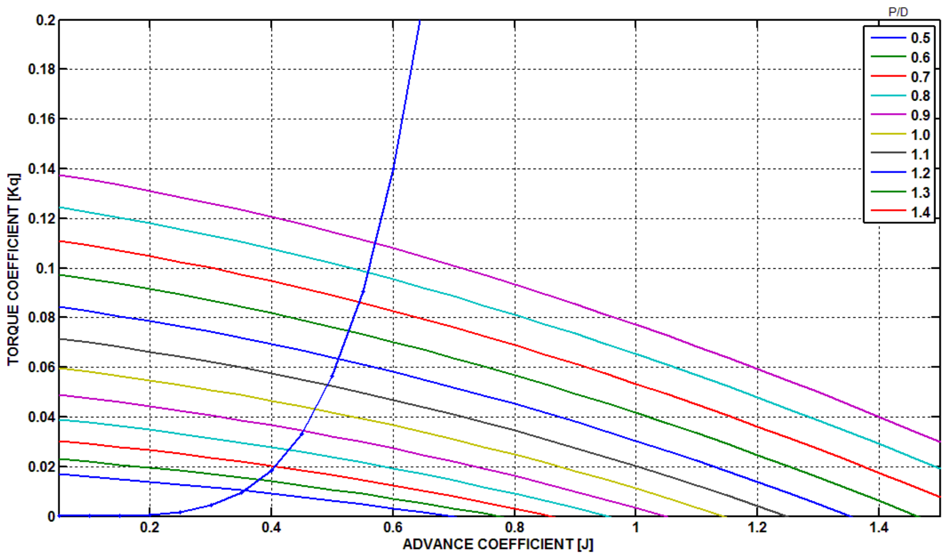


Figure 8. Intersection of Kq curves

Extracting values of intersection and computing thrust coefficient, open water efficiency and diameter, table 4 can be constructed.

Table 7. Intersection points between curves with corresponding diameter (n=124.5 rpm)

P/D	J	Kt	Kq	H	D (m)
0.5	0.3545	0.0884	0.0103	0.4842	6.299
0.6	0.3785	0.1252	0.0147	0.5131	5.900
0.7	0.4052	0.162	0.0201	0.5198	5.511
0.8	0.4275	0.2007	0.0267	0.5114	5.224
0.9	0.4521	0.2381	0.0344	0.4980	4.940
1	0.4711	0.2768	0.0432	0.4804	4.740
1.1	0.492	0.3134	0.0529	0.4639	4.539
1.2	0.51	0.3496	0.0634	0.4476	4.379
1.3	0.5263	0.3848	0.0747	0.4315	4.243
1.4	0.5431	0.4186	0.0863	0.4193	4.112

Selection of the final diameter is constrained by the space available for fitting the propeller. The gap between ship hull and propeller tip, is called clearance. We must comply with required propeller clearance to avoid and/or minimize vibrations problems at the stern of the ship. In this matter, DNV present basic rules for minimal distance of propeller regarding ship hull.

Det Norske Veritas recommendations for single screw ships:

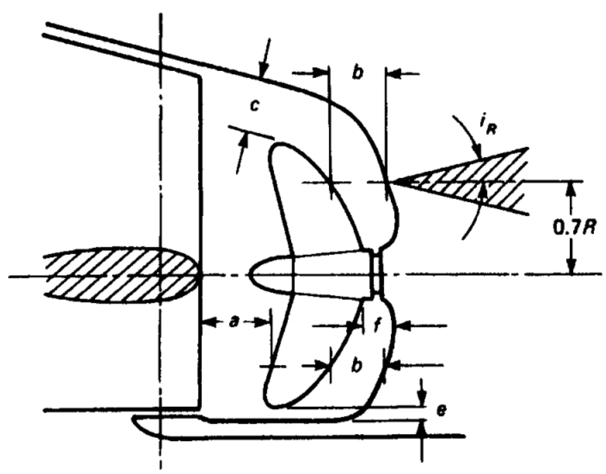


Figure 9. Propeller clearances for single screw ships (DNV)

Taken from Volker Bertram Ship design for efficiency and economy, page 63.

$a > 0.1D$

$b > 0.27D$

$c > 0.20D$

$e > 0.035D$

where D is the propeller diameter

An increase value of the clearance reduces noise on the ship due to propeller but reduces propeller diameter; a compromise between the two must be done.

Also, blade area ratio must be checked for every diameter to avoid cavitation, and we must compare new value of thrust with the required at design condition to achieve 14 knots. Results of computation are presented in table 7 below.

Table 8. Intersection points between curves considering clearance

P/D	J	Kt	Kq	η	D (m)	Thrust (kN)	EAR to avoid cavitation	Required clearance (m)	Space available (m)
0.5	0.3545	0.0884	0.0103	0.4842	6.299	614.86	0.43	1.260	1.001
0.6	0.3785	0.1252	0.0147	0.5131	5.900	670.09	0.49	1.180	1.400
0.7	0.4052	0.162	0.0201	0.5198	5.511	660.13	0.52	1.102	1.789
0.8	0.4275	0.2007	0.0267	0.5114	5.224	660.08	0.56	1.045	2.076
0.9	0.4521	0.2381	0.0344	0.4980	4.940	626.06	0.58	0.988	2.360
1	0.4711	0.2768	0.0432	0.4804	4.740	617.31	0.61	0.948	2.560
1.1	0.492	0.3134	0.0529	0.4639	4.539	587.53	0.62	0.908	2.761
1.2	0.51	0.3496	0.0634	0.4476	4.379	567.65	0.64	0.876	2.921
1.3	0.5263	0.3848	0.0747	0.4315	4.243	550.93	0.66	0.849	3.057
1.4	0.5431	0.4186	0.0863	0.4193	4.112	528.53	0.67	0.822	3.188

Maximum efficiency is highlighted on yellow. A diameter of 5.51 m was selected because it represents the highest open water efficiency among diameters that comply with minimum clearance rules.

For a graphical view of the results, figure 10 was created.

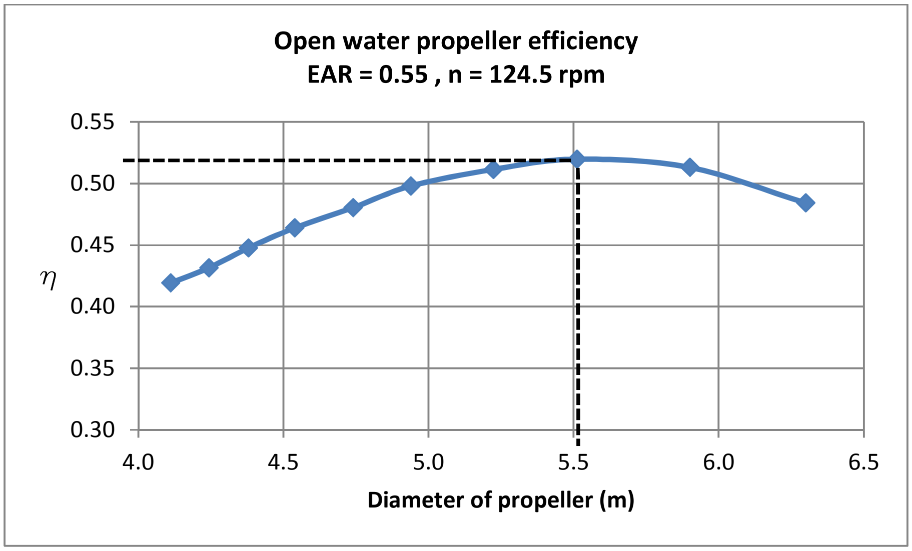


Figure 10. Efficiency vs. propeller diameter

Diameter, speed of rotation, number of blades, delivered power will provide the starting point for the actual design of the propeller.

Table 9. Optimal B-Wageningen standard series propeller for the ship

Propeller type	Fixed pitch B4-Wageningen series
Diameter (m)	5.51
EAR	0.55
Torque coefficient K_Q	0.01979

5.4 Ship speed estimation with preliminary propeller

One of owners' requirements is that the vessel is able to achieve a certain speed under power service less than maximum continuous power MCR of the engine.

Checking that the service speed complies with the design speed of the vessel is crucial in the design. Estimated velocity must be $\pm$ 2% of design speed.

Table 10. Prediction of performance characteristics of propeller at different speeds

Ship speed - V (knots)	13	14	15
Ship speed - V (m/s)	6.6872	7.2016	7.716
Velocity of advance – Va (m/s)	4.3046	4.6357	4.9668
Advance coefficient – J	0.3763	0.4053	0.4342
Kq	0.01979	0.01979	0.01979
P/D	0.675	0.69	0.715
η_o	0.499	0.521	0.553
Kt	0.165	0.16	0.1585
Thrust (kN)	671.73	651.38	645.27
η_h	1.1603	1.1603	1.1603
η_r	1.0204	1.0169	1.0128
η_D	0.591	0.615	0.650
Effective power – Pe (kW)	2749.24	3514.38	4474.43
Delivered power – Pd (kW)	4651	5712	6880

Construction of a graph considering propeller delivered power vs. ship speed will determine:

- V – vessel speed achieved by propeller
- P / D – optimum propeller pitch ratio

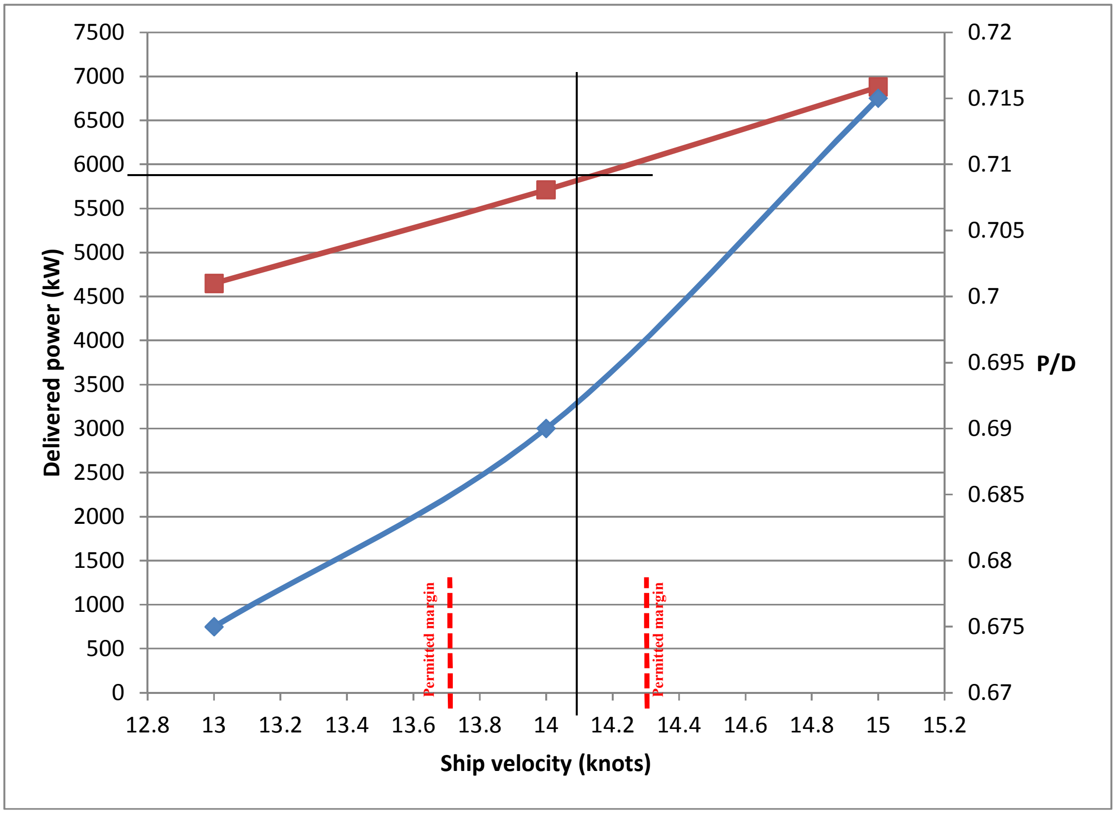


Figure 11. Ship velocity estimation according to delivered power to the propeller

From figure above, we can conclude that estimated speed will be approximately 14.1 knots using a propeller with a pitch ratio of 0.692.

Main geometrical parameters and hydrodynamic characteristics of the optimal B-Wageningen propeller are presented in table below:

Table 11. Main geometrical and hydrodynamic characteristics of optimal propeller

Propeller type	Fixed pitch B4-Wageningen series
Diameter (m)	5.51
P/D	0.692
EAR	0.55
Advance coefficient J	0.4081
Thrust coefficient K_T	0.157
Torque coefficient K_Q	0.01979
Open water efficiency	0.5153

Constructing the open water hydrodynamics characteristics of the propeller for complete range of speed we obtain.

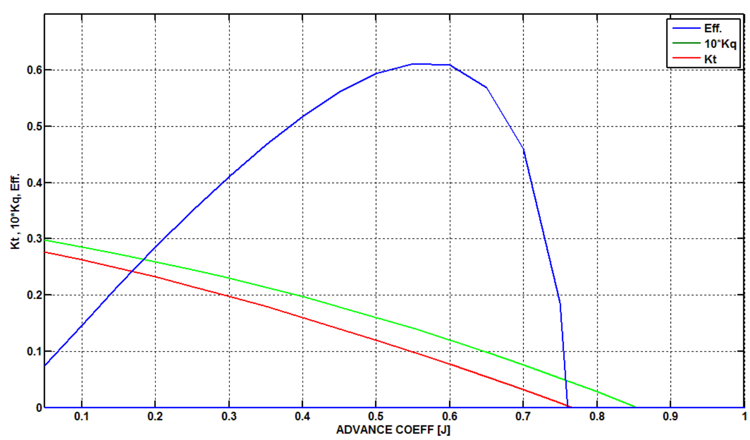


Figure 12. Open water propeller performance for the optimal B-Wageningen propeller

5.5 Cavitation check

Cavitation is the phenomenon that occurs when the local pressure is lower than vaporization pressure of water at a certain temperature, forming bubbles of air that collapse rapidly when the pressure increases again. Regarding propellers, because they deal with high speeds, according to Bernoulli's equation, the pressure decreases and it may sometimes induce cavitation on propellers blades.

Negative effects can arise on a cavitating propeller, such as vibration, noise, material erosion on propeller surface, and thrust reduction. Avoidance of cavitation and erosion is an important aspect in the design of any propeller. At preliminary stage, the use of Burill diagrams provides a lower limit of blade area ratio to reduce the danger of cavitation appearance.

Procedure for obtaining minimum blade area ratio is presented below as follows:

Calculation of cavitation number:

$$\sigma_A = \frac{p_o - e}{0.5\rho {V_A}^2} = \frac{p_{at} + \gamma h - e}{0.5\rho[V(1-w)]^2} = \frac{101300 + 10052 * 6.85 - 2353}{0.5 * 1025[4.64]^2} = 15.24$$

Where h is the propeller immersion in meters; obtained using the vessel lines plan.

$$\delta = \frac{101.3}{J} = \frac{101.3nD}{V_A} = \frac{101.3 * 2.07 * 5.51}{4.64} = 249.94$$

$$\gamma_7 = 1 + \left(\frac{\delta}{46.1}\right)^2 = 1 + \left(\frac{249.94}{46.1}\right)^2 = 30.39$$

$$\sigma_R = \frac{\sigma_A}{\gamma_7} = \frac{15.24}{30.39} = 0.50$$

Absolute value of local velocity at 0.7 of the propeller radius:

$$V_{0.7} = \sqrt{{V_A}^2 + (0.7\pi nD)^2} = \sqrt{4.64^2 + (0.7\pi * 2.07 * 5.51)^2} = 25.58\frac{m}{s}$$

Thrust loading coefficient:

$$K_v = \frac{T}{\rho D^2 {V_{0.7}}^2} = \frac{653367.25}{1025 * 5.51^2 * 25.58^2} = 0.0321$$

Applying a safety factor of 20% to the cavitation number we obtain:

$$\sigma_R = 0.8 * 0.50 = 0.401$$

Figure 13 shows a Burill diagram. Marked with black lines is the procedure to find the required developed area ratio. Starting from the thrust loading coefficient, you approach the curves from cavitation number, descend perpendicularly to the mean pitch ratio of the propeller and cross in a 90 degrees angle (to right) to obtain developed area ratio.

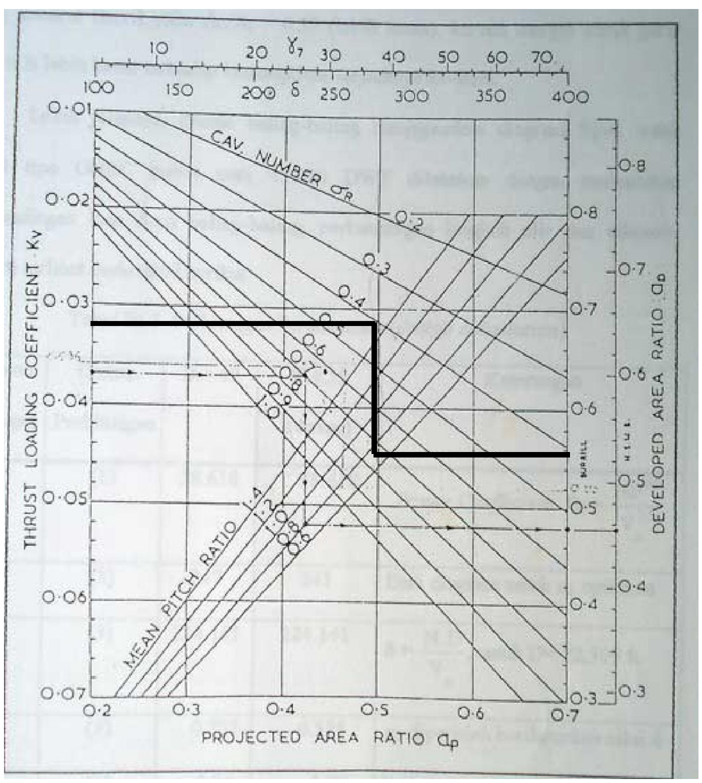


Figure 13. Burill diagram.Taken from http://charlesroring.blogspot.ro/2010/05/propeller-blade-area-ratio.html (visited 17 january 2013)

From figure above we obtain a developed area ratio of approximately:

$$a_D = 0.56$$

Finally expanded area ratio is given by the expression:

$$a_e = 0.34a_D\left(2.75 + \frac{a_D}{z}\right) = 0.55 = \frac{A_E}{A_o}$$

Our propeller expanded area ratio is sufficient to minimize the risk of cavitation.

Up to this point, propeller has been designed to operate in a mean global wake, using B-Wageningen diagrams to consume a delivered power at a specified rotation rate. Results present good agreement between shaft power, propeller revolution rate and ship speed. On the other hand, performances of a propeller based on systematic series are insufficient for today's expectation because no account is taken for the variation of the wake over the propeller disc.

Propeller geometry necessary for fulfilling our requirements is still unknown. Next section present analytical methods to design the so called wake adapted propeller.

5.6 Lifting line theory in propeller design

There are various theories for predicting propeller action: momentum theory, blade element theory, circulation theory, boundary element method, and RANS method.

Modern theories such as lifting line theory are based on circulation theory. According to this theory, lift produced by each propeller blade is explained in terms of circulation around it, in a manner similar to the lift produced by an aircraft wing. The flow past a blade can be regarded as composed of a uniform flow of velocity V and a vortex circulation Γ.

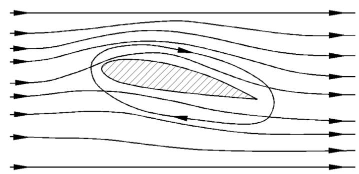


Figure 14. Flow around a wing composed by a uniform flow and a vortex

Because of asymmetry of the velocity distribution (upper side and lower side), there is also asymmetry in pressure distribution, as a result, a lift is exerted on the blade.

Propeller blade is represented by a system of vortex lines or lifting lines, and the induced velocities in the propeller plane can be calculated without knowing the propeller geometry.

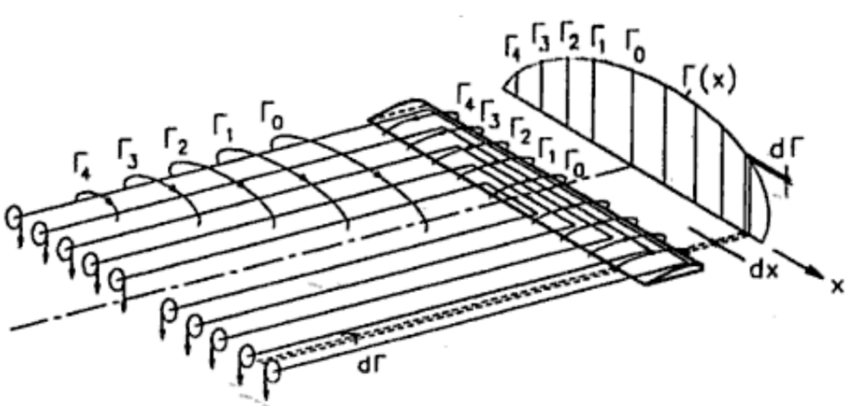


Figure 15. Representation of bound vortex and trailing vortex in an airfoil.

Taken from lectures notes of Ship Propulsion course at UGAL 2013.

Lift characteristics of the section are now described by the circulation Γ.

Propeller design using lifting line theory can be divided in two stages:

1. As a first step, the circulation, induced velocities, resultant velocity and the hydrodynamic pitch at various radiuses are calculated.

2. The optimum blade geometry is determined from the point of view of cavitation suppression and strength criteria.

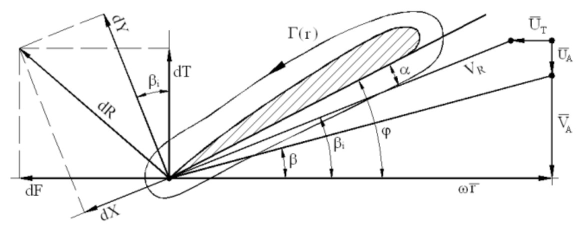


Figure 16. Velocity diagram for a blade section.

Taken from lectures notes of Ship Propulsion course at UGAL 2013.

where α is the angle of attack, β the advanced angle, βi hydrodynamic pitch angle, δ the final pitch angle.

From figure 16 relations between induced velocities are determined:

$$v = \sqrt{(V_A + U_A)^2 + (wr - U_t)^2} \quad (12)$$

$$\frac{U_A}{V_A} + tg(\beta_i)\frac{U_T}{V_A} = \frac{tg(\beta_i)}{tg(\beta)} - 1 \quad (13)$$

Velocity induced by the vortex system of the propeller can be computed by the law of Biot Savart or by Laplace equation. For practical methods, induction factor have been develop to simplify the solution.

The thrust developed by the blade element and the torque are computed as function of the circulation Γ(r).

for the thrust:

$$T = \rho z \int_{r_b}^{R} \Gamma(r)(wr - U_T)\big(1 - \varepsilon tg(\beta_i)\big)dr \quad (14)$$

for the torque:

$$Q = \rho z \int_{r_b}^{R} \Gamma(r)(V_A + U_A)\left(1 + \frac{\varepsilon}{tg(\beta_i)}\right) rdr \quad (15)$$

Solving for the vortex strength distribution, convergence is obtained when the trust coefficient computed equalizes the thrust coefficient data.

Thrust coefficient:

$$C_{T_i} = 4z \int_{r_b}^{1} G\big(1 - w(r)\big)^2 \left(\frac{1}{tg(\beta)} - \frac{U_T}{V_A}\right) dr = \frac{8T_i}{\pi \rho V^2 D^2}$$

After final values of circulation, Ua, Ut and hydrodynamic pitch angle are computed, the geometrical design can be started.

Lift coefficient depends on type of airfoil section, camber ratio, thickness to chord ratio and the angle of attack. The problem is to select a combination of the above to match the data from hydrodynamic design stage.

5.6.1 Lifting line theory computation

Main objective is to find blade geometry for a specified radial distribution of the loading. As it is a wake adapted propeller, we need to introduce the value of the wake of the ship. This information was provided by ICEPRONAV Engineering and exact values are not included on the text for confidentiality reasons.

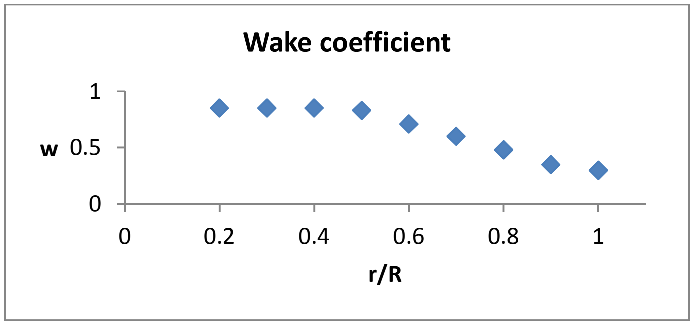


Figure 17. Mean circumferential wake coefficient

To proceed with calculation using and in-house code developed at the University of Galati at the department of Naval Architecture we need to introduce the following data:

Table 12. Input data for lifting line code

Delivered power (kW)	5791
Propeller diameter (m)	5.51
RPM	124.5
Number of blades	4
Skew (degrees)	21
Water density (kg/m^3)	1025

The propeller skew was imposed to reduce the propeller induced exciting forces acting on the ship, and to minimize risk of cavitation. Also, the skewing makes little difference to the efficiency.

Table 13. Main results from lifting line theory

Ship speed (knots)	14.24
Thrust (kN)	684.47
Torque (kNm)	450.75
Advance coefficient J	0.4123
Kt	0.1683
Kq	0.0201
Efficiency	0.5458
P/D	0.6359

According to section 5.6, axial and tangential velocities for the converged solution are shown en table 12. Notice the high velocity values near the tip of the propeller.

Table 14. Velocities computed using lifting line theory

r/R	Ua/Vr	Ut/Vr	Vr
0.2	1.568	1.8059	1.1993
0.3	0.6645	0.4538	10.8769
0.4	0.7636	0.3965	14.3713
0.5	0.7898	0.3286	17.9662
0.6	0.6502	0.2296	21.6977
0.7	0.5386	0.1649	25.3932
0.8	0.4308	0.1167	29.0811
0.9	0.3299	0.0799	32.7654
1	1.3513	0.2933	34.9703

As stated in section 5.6, lift coefficient depends on geometrical characteristics of the airfoil section and the angle of attack. The solution obtained is shown in table below:

Table 15. Propeller geometrical characteristics

r/R	Thickness (mm)	Chord (mm)	Camber (mm)	P(r) (m)	Xa (mm)
0.2	232.7	1461.2	73	3.5443	730.6
0.3	199.8	1617.2	68.6	3.7531	795.3
0.4	169.3	1757.3	46.8	3.6802	825.2
0.5	140.5	1875.2	39.9	3.6118	815.9
0.6	114	1961	35.8	3.6671	760.3
0.7	89.1	1996.2	32.6	3.7043	645.5
0.8	65.3	1942.6	30.5	3.7382	446.9
0.9	43.2	1693.2	31.1	3.7387	101.2
0.95	32.6	1275	21.05	3.7473	-241.8
0.975	27.3	900	16.025	3.7516	-503.5
0.985	24.12	680	13.01	3.7542	-644.7
1	22	0	11	3.7559	-1033.2

Propeller strength is a major concern in propeller design due to blade stresses. Minimum thicknesses values at relative radius 0.25 and 0.6 are imposed by classification society's rules. Checking compliance with these rules is available in the Appendix section *Propeller strength calculations*.

Moving on, blade shape is defined by a series of sections, each formed by the intersection of the blade with circular cylindrical surface of radius r coaxial with the axis of rotation. In order to construct the two dimensional profile, we will use NACA 66 profile (see in Appendix NACA 66) in combination with the equations:

$$Y+ = F_t * t + F_c * f_m \qquad (16)$$

$$Y- = -F_t * t + F_c * f_m \qquad (17)$$

where t is the thickness,

f_m *is the radial distribution of camber,*

F_c *is the type of camber distribution,*

F_t *is the type of thickness distribution,*

A Matlab application that introduces the values of NACA profile into equations 16 and 17 was developed to create the 2D geometry of blade sections. Expanded blade form of the final propeller blade is presented in next figure.

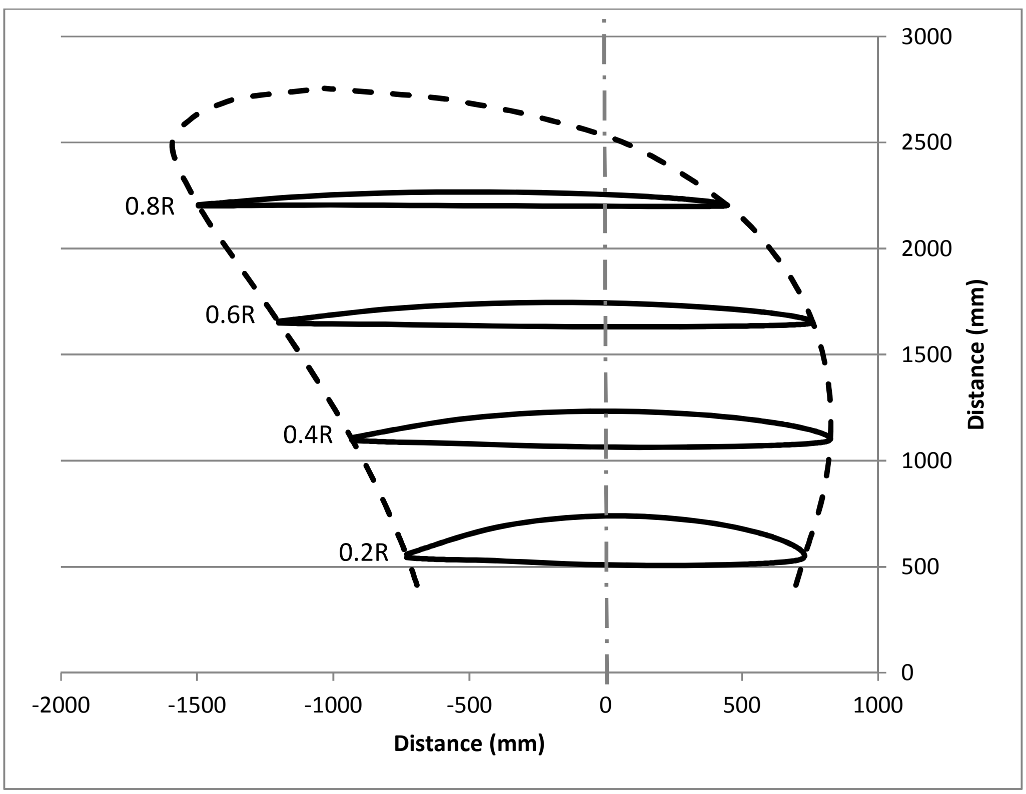


Figure 18. Expanded blade form for the wake adapted propeller

Important is to notice the effect of the skew imposed in the input data for the lifting line code. Final step in generating propeller geometry, is creating the 3D shape of the blade. To achieve this, we will based on two pair of equations as follows:

- For the upper side:

$$\bar{x}^{+} = \bar{x}_R + (\bar{c}_s + \bar{c}\tilde{\varepsilon})\sin\varphi + \left(\bar{f}_m F_c + \bar{e}F_T\right)\cos\varphi \qquad (18)$$

$$\theta^{+} = \frac{1}{r}\left[(\bar{c}_s + \bar{c}\tilde{\varepsilon})\cos\varphi - \left(\bar{f}_m F_c + \bar{e}F_T\right)\sin\varphi\right] \qquad (19)$$

- For the lower side:

$$\bar{x}^{-} = \bar{x}_R + (\bar{c}_s + \bar{c}\tilde{\varepsilon})\sin\varphi + \left(\bar{f}_m F_c - \bar{e}F_T\right)\cos\varphi \qquad (20)$$

$$\theta^{-} = \frac{1}{r}\left[(\bar{c}_s + \bar{c}\tilde{\varepsilon})\cos\varphi - \left(\bar{f}_m F_c - \bar{e}F_T\right)\sin\varphi\right] \qquad (21)$$

$where\ \bar{x}_R\ is\ the\ radial\ distribution\ of\ rake,$

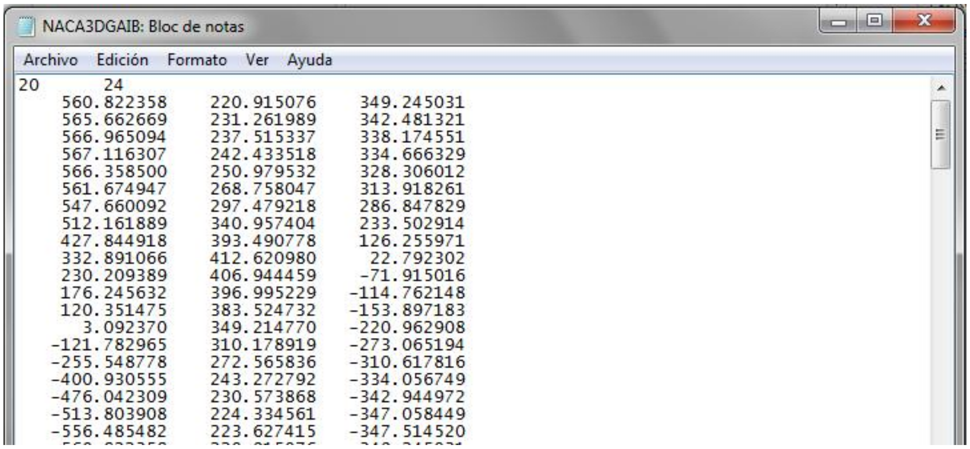
$\bar{c}_s\ is\ the\ radial\ distribution\ of\ skew,$

$\bar{e}\ is\ the\ radial\ distribution\ of\ maximum\ thickness,$

$\bar{c}\ is\ the\ radial\ distribution\ of\ chord\ length,$

$\tilde{\varepsilon}\ is\ given\ by\ the\ NACA\ profile,$

Using an in house code developed at University of Galati in the department of Naval Architecture, hundreds of vertexes points are obtained that contain the propeller 3D shape by sections.


NACA3DGAIB: Bloc de notas

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20        24
     560.822358     220.915076     349.245031
     565.662669     231.261989     342.481321
     566.965094     237.515337     338.174551
     567.116307     242.433518     334.666329
     566.358500     250.979532     328.306012
     561.674947     268.758047     313.918261
     547.660092     297.479218     286.847829
     512.161889     340.957404     233.502914
     427.844918     393.490778     126.255971
     332.891066     412.620980      22.792302
     230.209389     406.944459     -71.915016
     176.245632     396.995229    -114.762148
     120.351475     383.524732    -153.897183
       3.092370     349.214770    -220.962908
    -121.782965     310.178919    -273.065194
    -255.548778     272.565836    -310.617816
    -400.930555     243.272792    -334.056749
    -476.042309     230.573868    -342.944972
    -513.803908     224.334561    -347.058449
    -556.485482     223.627415    -347.514520
```

Figure 19. Fragment of vertex file

Vertexes points are organized in x , y , z coordinates. On the first row, the number 20 corresponds to the number of points that conform a line, and number 24, is the number of lines that define the section. Importing the vertex in the software GAMBIT, is possible to generate the view of the propeller blade, which will be the starting point to generate the complete propeller shape.

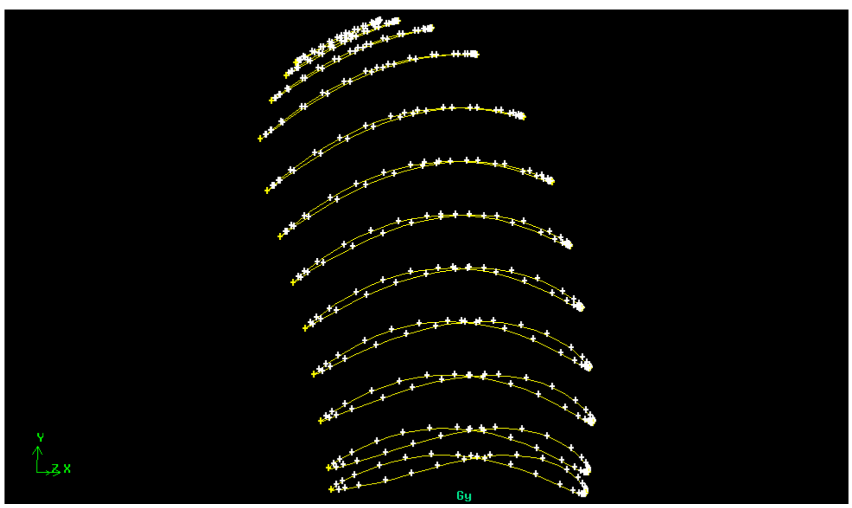

Figure 20. Vertex data imported in Gambit with edges

6. CFD CALCULATIONS FOR FINAL PROPELLER

6.1 Theoretical background

Before the appeareance of CFD, to validate propeller performances was necessary to undertake experimental validation of the model propeller. Large amount of time and economical investment was needed. If unsatisfactory results where obtained, propeller design loop started again requiring new models and new experiments.

Obviosly, new tools for validation where required to avoid the inconvenience of model experiments. In recent years, CFD computation represents a valid solution for evaluating performances of hulls, propellers, etc. Main advantages of CFD over experimental approach are the following:

- Relative low cost: Experimental test can be expensive. CFD simulation is relatively inexpensive.
- Speed: CFD calculations can be made in a short period of times. Operating and model conditions can be changed rapidly to evaluate various cases.
- They simulate real conditions: CFD theoretically simulates any physical condition.
- Ideal conditions: control over the physical process is extensive.

Limitations of CFD are the solution dependance upon physical model used, accuracy goes as far as the physical model they rely on, and boundary conditions play a significant role in the solution, among others. Also, important is to fully understand that numerical simulation is a complementary tool to provide data to experimental and theoretical data.

Main ideas having said, CFD role in propeller design is used as a hydrodynamic performance validation tool.

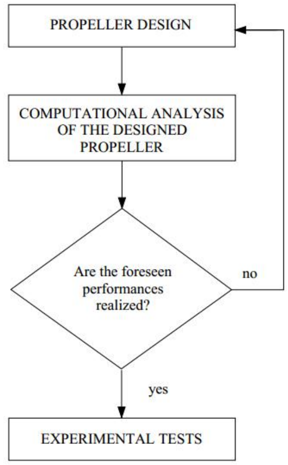

Figure 21. CFD role in propeller design.

Taken from lectures notes of Ship Propulsion course at UGAL 2013.

Using CFD codes is possible to identify problems early in the design stage, and to evaluate changes rapidly.

After propeller detailed design is finished, propeller performances are investigated numerically in steady and unsteady flow. Steady analysis consist of calculation of open water characteristics and calculation of the pressure distribution on propeller blades operating in uniform flow or in a radially varied circumferential mean flow. Unsteady analysis comprises of calculation of the pressure distribution on propeller blades in various blade positions and cavitation prediction, calculation of the unsteady forces and moments acting on propeller shaft and finally, calculations of the hull pressure distribution.

6.2 Shipflow

The software Shipflow is specialized for naval applications. It uses a finite volume code that solves the Reynolds Average Navier Stokes equation. Also it relies on potential methods to solve specific problems. It uses the approach of actuator disk with a lifting line model to simulate the propeller action.

Interactive coupling between the RANS solver and lifting line method is achieved through body forces accelerating the flow. Results depend on blade geometry such as: camber ratio, pitch ratio, blade thickness and chord length [8].

Main computation was done for open water characteristics. Developed Shipflow command file can be found in Appendix section.

Results for computation are below:

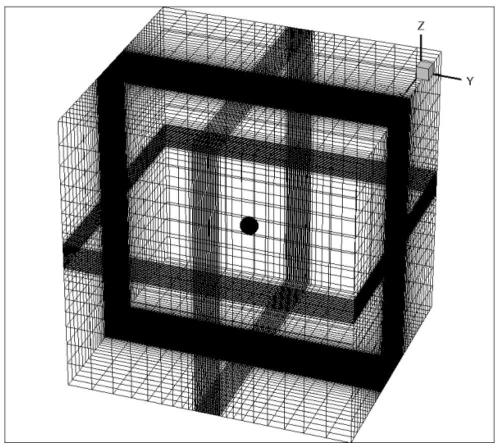

Figure 22. Mesh generated by default using Shipflow

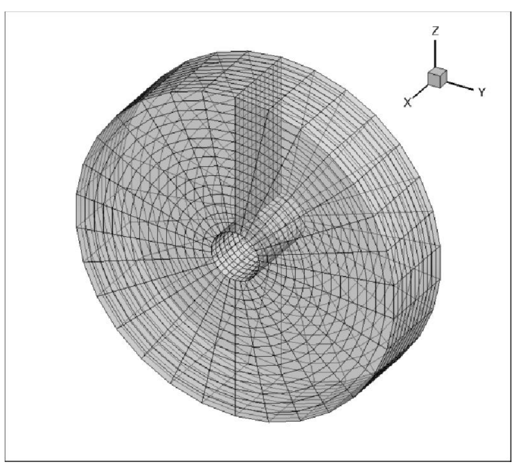

Figure 23. Propeller grid

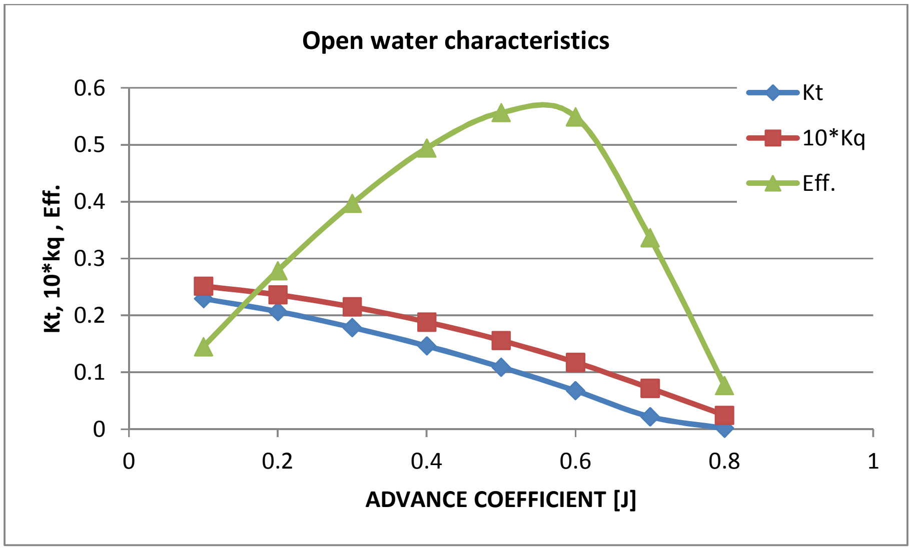

Figure 24. Open water characteristics of final propeller computed by Shipflow

For numerical validation, open water results will be compared with another CFD code. Although other authors state that differences of 1-2% have been obtained when compared to experimental data [8].

6.3 Fluent

We can divide the methodology in four basic steps as follows:

1. Geometry generation
2. Mesh generation
3. Calculation using RANS software
4. Post-processing

Propeller geometry and mesh were generated using the commercial software Gambit. A size function was attached near the propeller surface to increase the density of the cells at this area.

For computation, we selected two cases for velocity distribution:

1. Uniform flow (open water).
2. User defined function for velocity inflow (relative to radial wake estimations)

A study of grid influence was performed to discard any grid dependency on the solution obtained. Three different meshes were evaluated.

Finally, comparisons between Fluent and Shipflow for open water characteristics were undertaken to validate numerical results, and comparisons between Fluent and lifting line were done for the wake adapted propeller.

6.3.1 Geometry and mesh generation using GAMBIT

After vertex data is imported into Gambit, trailing and leading edges are created. From the enclosed area is possible to generate the face and the back of the propeller blade. Afterwards, creation of a volume is made by connecting the closed faces with the blade section at 0.15 radius.

To create all propeller blades, three copies of the blade are made and separated with a 90 degrees angle between them. Generated propeller is completed by including the boss. Finally, a large shaft is created to ensure the uniformity of flow entering the propeller plane.

To eliminate scale effects, propeller was created 1:1.

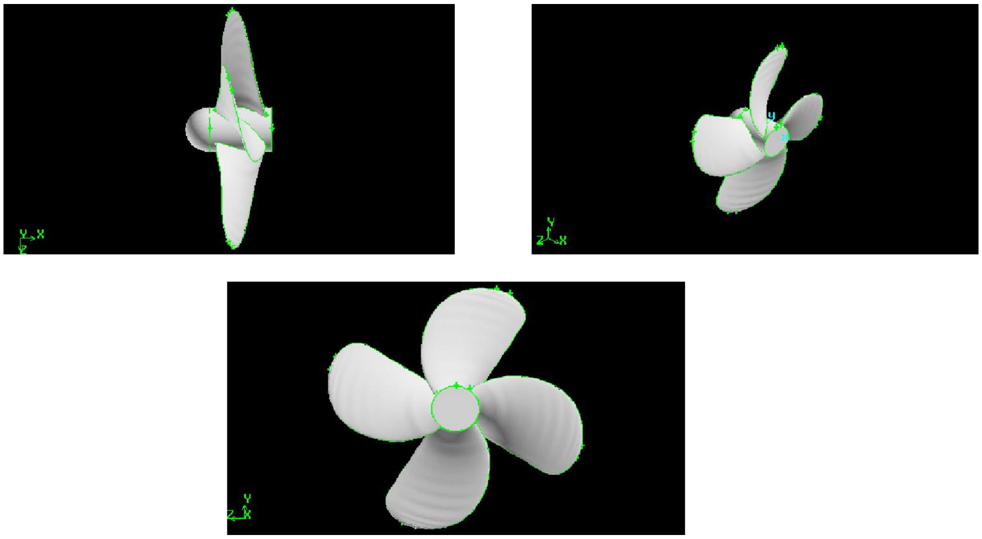

Figure 25. Propeller geometry in GAMBIT

Because of complex phenomena to study, we will use nonstructural mesh with a size function around the propeller and shaft surface to increase the density of cells near to these regions.

As a domain, we will use a cylindrical shape with the following dimensions:

- A radius of 2.5*D
- Beginning at 1.8*D ahead of the propeller plane
- Ending located at 4*D behind the propeller.

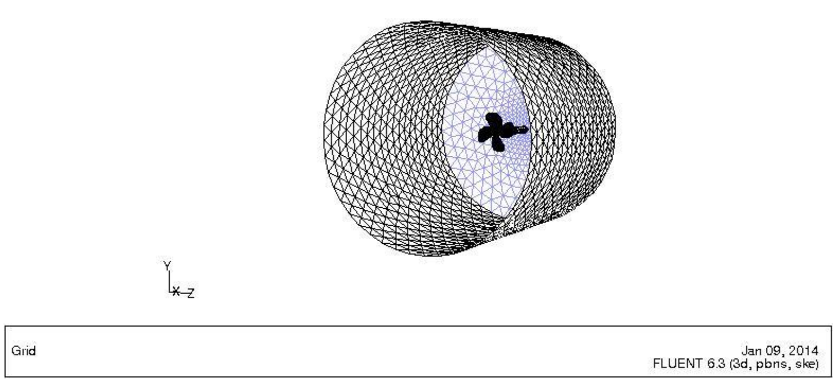

Figure 26. Perspective view of domain

From which the propeller volume is subtracted and the final domain is created. At this point, a mesh export from Gambit to Fluent is performed.

6.3.2 Set up of numerical model in FLUENT

After importing the mesh file into the CFD code, we need to define:

1. *Selection of appropriate physical models*: Standard k-e model with standard wall functions. Velocity and pressure coupling was set to SIMPLE.
2. *Define material properties*: the fluid was set to be liquid water with a density of 1025 kg/m^3
3. *Prescribe operating conditions*: velocity of rotation of the fluid domain was set at 124.5 rpm.
4. *Prescribe boundary conditions at all boundary zones:*
    - Inlet: was set to velocity inlet, with a turbulence specification method of Intensity and Hydraulic diameter.
    - Outlet: was set to pressure outlet, with a radial equilibrium pressure distribution and a turbulence specification method of Intensity and Hydraulic diameter.
    - Propeller and shaft: were set to wall.
    - Surroundings: was set to be a non-rotating wall

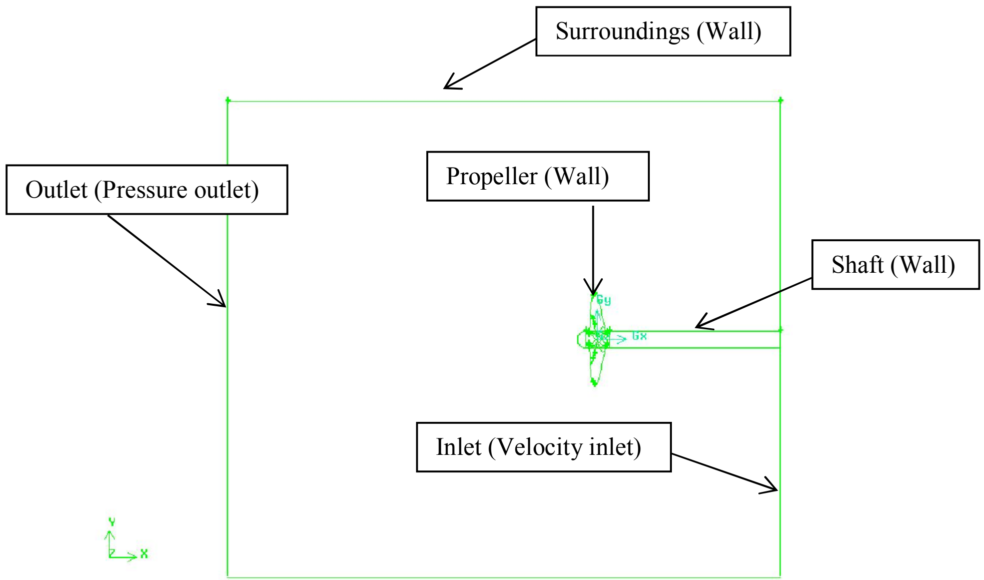

Figure 27. Boundary conditions for the domain

5. *Setting up of solver controls:* under-relaxation factors for Turbulence Kinetic Energy and Turbulence dissipation rate were set to 0.6. Discretization for Momentum, Turbulence Kinetic Energy and Turbulence Dissipation Rate were set to Second Order Upwind.
6. *Set up convergence monitors:* for mathematical criteria, residuals were set to 10^{-4}. Fluctuation and stability of drag coefficient was used as physical criteria to ensure convergence.

6.3.3 Results

In this section results of Fluent computation are presented. The advance coefficient was changed by changing the velocity inflow, to be able to investigate the characteristics in all propeller operating points.

Convergence of the solution was established by observing the stability of the drag coefficient at the propeller and the residuals.

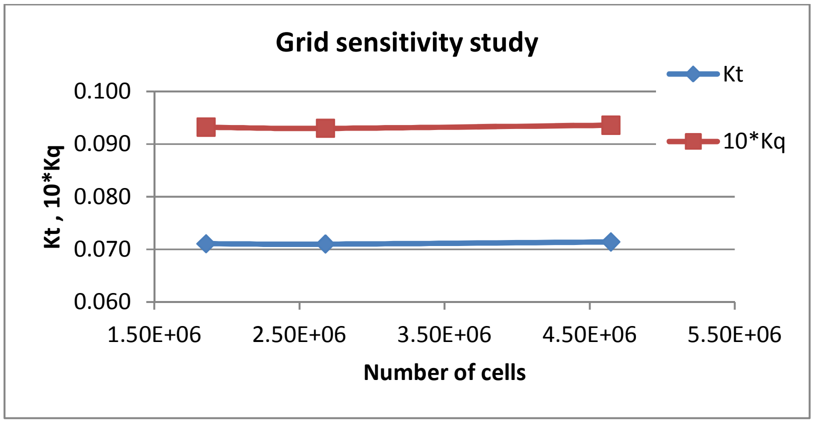

Figure 28. Thrust and torque coefficients for different meshes

Changing the number of cells does not have influence in the numerical results. For computation, a mesh of 1.8E+06 was used. It has been shown that usage of non-structured mesh presents good results for propeller evaluation [9].

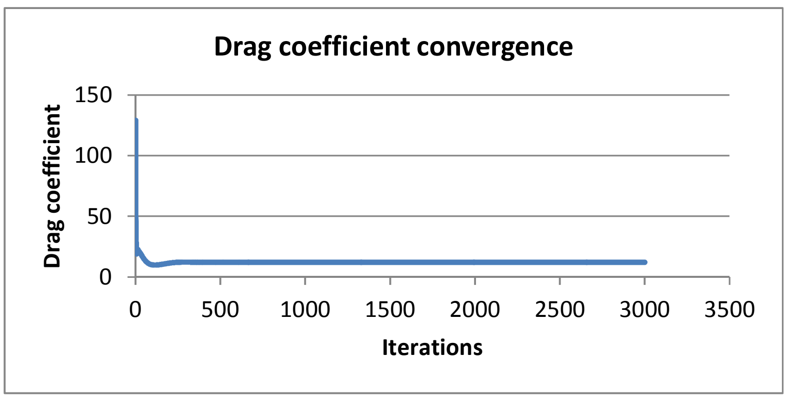

Figure 29. Drag coefficient

For all computations performed, drag coefficient stabilized in a similar manner has shown in figure above.

As stated before, open water characteristics where computed by the two methods. Table 14 present a summary of results with respective difference between values obtained.

Table 16. Open water characteristics computed by different CFD codes

	Kt			10*Kq		
J	Shipflow	Fluent	Difference	Shipflow	Fluent	Difference
0.2	0.2068	0.2387	15.3870	0.2362	0.2446	3.5385
0.3	0.1787	0.2008	12.3498	0.2150	0.2123	1.2404
0.4	0.1462	0.1602	9.5895	0.1883	0.1768	6.1272
0.5	0.1090	0.1170	7.3384	0.1559	0.1372	11.9825
0.6	0.0675	0.0709	5.1246	0.1173	0.0929	20.7994

For a graphical view, figure 30 was built.

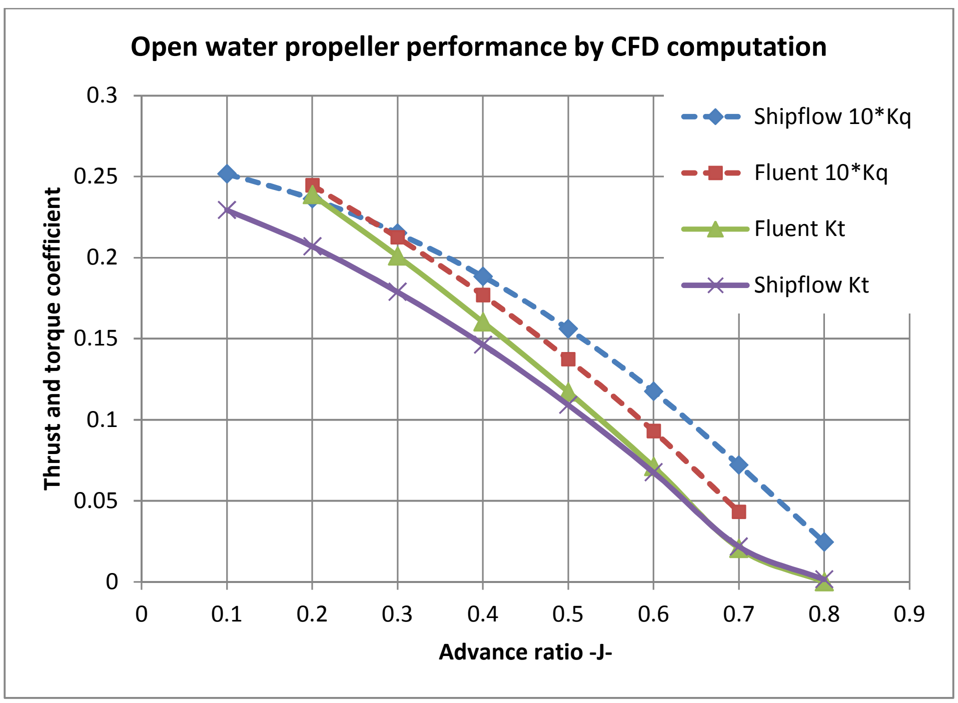

Figure 30. Open water characteristics computed with two different CFD methods

For a value of J = 0.6, thrust coefficient difference between the two methods is 5.12%. For a J = 0.2, torque coefficient difference is 1.24%. From figure above we can conclude that for low values of advance velocities (<0.5) torque coefficient is in good accordance, and for high values (>0.5) thrust coefficient is in good accordance.

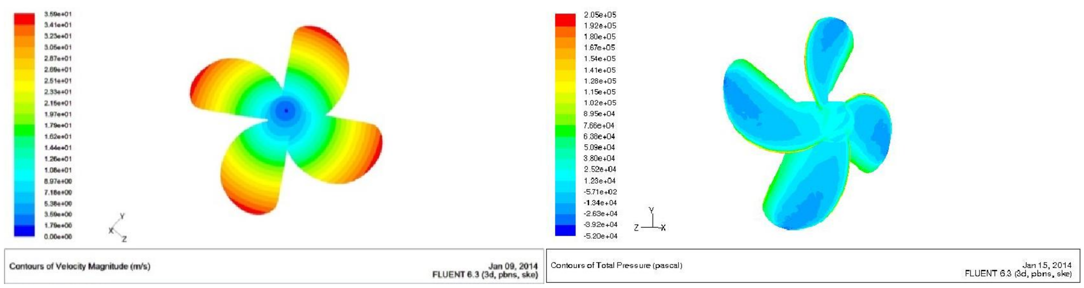

Figure 31. Velocity and total pressure on propeller blades at J =0.6

For velocity, good representation of physical phenomena was obtained; notice velocity magnitude at the propeller tip, it is maximum as theory states. Right figure is showing an increased pressure at the leading edges as expected and a low pressure in the suction side of the propeller blade.

Poor distribution of pressure in propeller blade is due to incorrect Y+ values due to the meshing, but global results are more accurate.

A user defined function, or UDF, is a C function that can be dynamically located with the Fluent solver to enhance its standard features [6]. We will use it to modify the inlet boundary condition from uniform velocity to a radially variable inlet velocity to simulate the effect of ship wake.

Creation of the function (see Appendix section) was done in Microsoft Word Notepad. Fluent code has a C compiler already integrated. Results of hydrodynamic performance for this case will be compared from those obtained with lifting line theory.

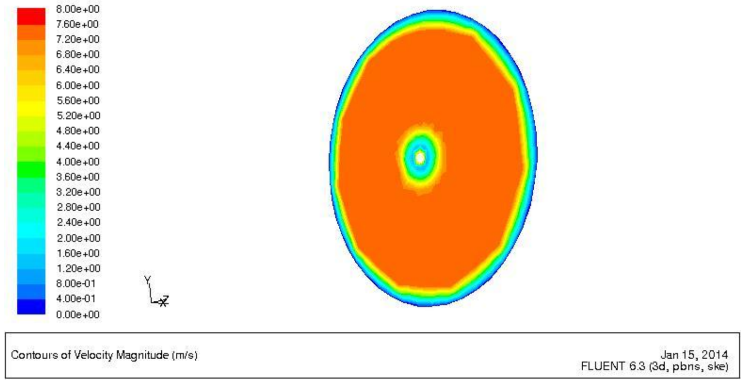

Figure 32. Variable velocity inlet profile

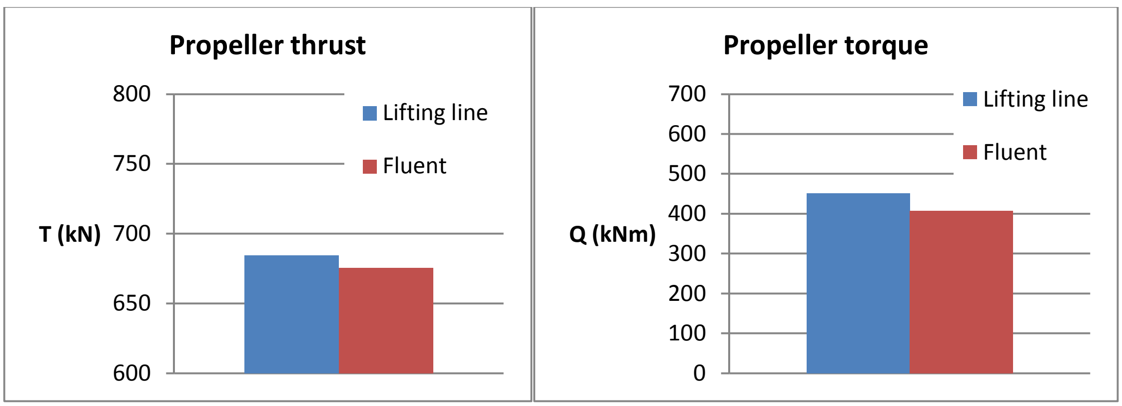

Figure 33. Propeller thrust and propeller torque

Both calculations have been performed for the design point of the propeller and for the same radial distribution of the circumferential mean flow. Results present a thrust difference of 1.32% and a torque difference of 9.7%

7. DESIGN OF SHAFTLINE

7.1 General considerations

A shaft is a rotating member, usually of circular cross section, used to transmit power or motion [4]. On a ship, the transmission system transmits power from the engine to the propeller; it is made up of shafts, bearings, and finally the propeller itself.

Main propulsion shafting system must accomplish a number of objectives, transmit the power output of the engine to the propulsor, support the propulsor, transmit the thrust, withstand operating loads, be free of modes of vibrations and provide reliable operation throughout the operating range [3].

Selection of shaft material will be based on strength, to ensure reliability of the system when operating. Forged steel is often selected for medium range power merchant vessels such as our bulk carrier. Dimensioning will be calculated using classification societies rules.

Bearings are used to support shaft and components weight. In our case, we will count with three bearings, the forward and aftermost stern tube bearings and the main thrust bearing. The first one will help sustain propeller weight and the latest will transmit the axial force of the propeller (thrust) to the ship hull through a foundation. Locations of mentioned bearings were decided considering space arrangements, ship’s fixed structures and bearing unit loads.

Shaft coupling will be performed via forged flange coupling with headed bolts. The aft end of the propeller shaft will be prepared for fitting the keyless propeller and hydraulic nut and a shaft grounding device with silver alloy band to be provided to electrically connect the shafting to the hull for the reduction of voltage difference between them.

7.2 Calculation of shaft line

Calculations according to GL Rules and regulations for the classification of ships, July 2008, Part 5, Chapter 6

The symbols used in next section are defined as follows:

$P\ shaft\ power\ in\ kW$

$R\ corresponding\ revolutions\ per\ minute$

$F\ coefficient\ according\ to\ installation\ type$

$k\ coefficient\ according\ to\ type\ of\ connection$

$\sigma_u\ specified\ minimum\ tensile\ strength\ of\ the\ material, in\ N/mm^2$

$n\ number\ of\ bolts\ in\ the\ coupling$

$D\ pitch\ circle\ diameter\ of\ bolts, in\ mm$

Intermediate shaft

$$d = F * k * \sqrt[3]{\frac{P}{R}\left(\frac{560}{\sigma_u + 160}\right)}$$

$$d = 100 * 1 * \sqrt[3]{\frac{8280}{129}\left(\frac{560}{600 + 160}\right)} = 361.64\ mm$$

Propeller shaft

$$d_p = 100k\sqrt[3]{\frac{P}{R}\left(\frac{560}{\sigma_u + 160}\right)}$$

$$d = 100 * 1.22 * \sqrt[3]{\frac{8280}{129}\left(\frac{560}{600 + 160}\right)} = 441.2\ mm$$

<u>Coupling bolts</u>

$$d = \sqrt{\frac{240}{nD}\frac{10^6}{\sigma_u}\frac{P}{R}}$$

$$d = \sqrt{\frac{240}{(10)(590)}\frac{10^6}{600}\frac{(8280)}{(129)}} = 65.96\ mm$$

7.3 Results

Geometry of the shaftline was generated using the software AUTODESK Inventor 2011. An isometric view of the shaft is presented below:

Figure 34. Isometric view of assembly with engine plate (without foundations)

Complete shaft drawings are available in Appendix section.

8. CONCLUSIONS AND RECOMMENDATIONS

- A complete propulsion system was designed from propulsive power estimation to propeller analysis using CFD codes.
- Design of a propeller is an iterative process. It should be adjusted to new constrains, cavitation avoidance, etc. If final propeller does not attain expected performances, a new design with a new geometry must be done.
- Lifting line theory offers good results for the design of a wake adapted propeller and also for open water propeller analysis in CFD codes.
- Using Fluent, pressure distribution on propeller blade is not accurate if values of Y+ are high, but global performance can be trusted.
- For our case, propeller blade sections thickness generated by lifting line code complies with propeller minimum thickness required by classification society's.
- Comparisons of results between RANS and lifting line at propeller design point are in good agreement. A 1.32% difference on K_T and 9.7% difference on K_Q were obtained.

Recommendations

1. Obtain detailed data of the ship axial and tangential wake to study the propeller as a source of noise and vibrations.
2. Experimental validation is necessary to compare with numerical results.
3. Perform a dynamic analysis of the shaftline to obtain loads on supports.

9. REFERENCES

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[8] D. Knutsson, L. Larssson, 2011. Large area propellers, 3.

[9] J. Kulczyk, et al., 2007, Analysis of screw propeller 4119 using the Fluent system, Vol. VII, Archives of civil and mechanical engineering.

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APPENDIX

A1) Coefficients and terms of the Kt and Kq polynomials for the Wageningen B-screw series.

K_T $C^T_{s,t,u,v}$	s (J)	t (P/D)	u (A_E/A_O)	v (Z)
+0.00880496	0	0	0	0
-0.204554	1	0	0	0
+0.166351	0	1	0	0
+0.158114	0	2	0	0
-0.147581	2	0	1	0
-0.481497	1	1	1	0
+0.415437	0	2	1	0
+0.0144043	0	0	0	1
-0.0530054	2	0	0	1
+0.0143481	0	1	0	1
+0.0606826	1	1	0	1
-0.0125894	0	0	1	1
+0.0109689	1	0	1	1
-0.133698	0	3	0	0
+0.00638407	0	6	0	0
-0.00132718	2	6	0	0
+0.168496	3	0	1	0
-0.0507214	0	0	2	0
+0.0854559	2	0	2	0
-0.0504475	3	0	2	0
+0.010465	1	6	2	0
-0.00648272	2	6	2	0
-0.00841728	0	3	0	1
+0.0168424	1	3	0	1
-0.00102296	3	3	0	1
-0.0317791	0	3	1	1
+0.018604	1	0	2	1
-0.00410798	0	2	2	1
-0.000606848	0	0	0	2
-0.0049819	1	0	0	2
+0.0025983	2	0	0	2
-0.000560528	3	0	0	2
-0.00163652	1	2	0	2
-0.000328787	1	6	0	2
+0.000116502	2	6	0	2
+0.000690904	0	0	1	2
+0.00421749	0	3	1	2
+0.0000565229	3	6	1	2
-0.00146564	0	3	2	2

$R_n = 2 \times 10^6$

$C^Q_{s,t,u,v}$	s (J)	t (P/D)	u (A_E/A_O)	v (Z)
+0.00379368	0	0	0	0
+0.00886523	2	0	0	0
-0.032241	1	1	0	0
+0.00344778	0	2	0	0
-0.0408811	0	1	1	0
-0.108009	1	1	1	0
-0.0885381	2	1	1	0
+0.188561	0	2	1	0
-0.00370871	1	0	0	1
+0.00513696	0	1	0	1
+0.0209449	1	1	0	1
+0.00474319	2	1	0	1
-0.00723408	2	0	1	1
+0.00438388	1	1	1	1
-0.0269403	0	2	1	1
+0.0558082	3	0	1	0
+0.0161886	0	3	1	0
+0.00318086	1	3	1	0
+0.015896	0	0	2	0
+0.0471729	1	0	2	0
+0.0196283	3	0	2	0
-0.0502782	0	1	2	0
-0.030055	3	1	2	0
+0.0417122	2	2	2	0
-0.0397722	0	3	2	0
-0.00350024	0	6	2	0
-0.0106854	3	0	0	1
+0.00110903	3	3	0	1
-0.000313912	0	6	0	1
+0.0035985	3	0	1	1
-0.00142121	0	6	1	1
-0.00383637	1	0	2	1
+0.0126803	0	2	2	1
-0.00318278	2	3	2	1
+0.00334268	0	6	2	1
-0.00183491	1	1	0	2
+0.000112451	3	2	0	2
-0.0000297228	3	6	0	2
+0.000269551	1	0	1	2
+0.00083265	2	0	1	2
+0.00155334	0	2	1	2
+0.000302683	0	6	1	2
-0.0001843	0	0	2	2
-0.000425399	0	3	2	2
+0.0000869243	3	3	2	2
-0.0004659	0	6	2	2
+0.0000554194	1	6	2	2

A2) Propeller weight

An important weight to be supported by the shaft is that one provided by the propeller, noted by W_p. As we already developed propeller geometry including hub for CFD computations, we can obtain the volume of the propeller, and after considering the material density (Ni – Al – Br), we can compute propeller mass as follows:

$$V_{prop} = 2.862\ m^3 \qquad \rho = 7650\ \frac{kg}{m^3}$$

$$W_{prop} = V_{prop} * \ \rho = 21894.3\ kg$$

A3) Propeller strength

Calculations according to Bureau Veritas Rules for the classification of steel ships, Part C, Ch 1, Sec 8.

The symbols used in next section are defined as follows:

f material factor

$\rho = \dfrac{D}{H}$

H mean pitch of propeller, in m.

D propeller diameter, in m.

M_t continuous transmitted torque, in kN.m

N rotational speed of the propeller, in rev/min

δ density of blade material, in kg/dm^3.

B developed area ratio

h rake, in mm.

I expanded width of blade section at radius from propeller axis, in mm.

z number of blades

R_m minimum tensile strength of blade material, in N/mm^2.

Minimum thickness of blade section at the radius 0.25 from the propeller axis:

$$t_{0.25} = 3.2\left[f\,\frac{1.5*10^6*\rho*M_t+51*\delta*\left(\frac{D}{100}\right)^3*B*I*N^2*h}{I*z*R_m}\right]^{0.5}$$

$$t_{0.25} = 3.2\left[8.3\,\frac{1.5*10^6*(1.49)*(613)+51*(7.6)*\left(\frac{5.51}{100}\right)^3*(0.6359)*(1617.2)*(129)^2*(220.18)}{(1617.2)*(4)*(590)}\right]^{0.5}$$

$$t_{0.25} = 176.54\ mm$$

Minimum thickness of blade section at the radius 0.6 from the propeller axis:

$$t_{0.6} = 1.9\left[f\,\frac{1.5*10^{6}*\rho_{0.6}*M_{t}+18.4*\delta*\left(\frac{D}{100}\right)^{3}*B*I*N^{2}*h}{I_{0.6}*z*R_{m}}\right]^{0.5}$$

$$t_{0.6} = 3.2\left[8.3\,\frac{1.5*10^{6}*(1.48)*(613)+18.4*(7.6)*\left(\frac{5.51}{100}\right)^{3}*(0.6359)*(1617.2)*(129)^{2}*(220.18)}{(1961)*(4)*(590)}\right]^{0.5}$$

$$t_{0.6} = 94.23\ mm$$

A4) NACA 66 profile

ε	$(1-\varepsilon)/2$	Fc	Ft
1	0	0	0
0.995	0.0025	0.0235	0.0445
0.99	0.005	0.0423	0.0665
0.985	0.0075	0.0595	0.0812
0.975	0.0125	0.0907	0.1044
0.95	0.025	0.1586	0.1466
0.9	0.05	0.2721	0.2066
0.85	0.075	0.3657	0.2525
0.8	0.1	0.4482	0.2907
0.7	0.15	0.5869	0.3521
0.6	0.2	0.6993	0.4
0.5	0.25	0.7905	0.4363
0.4	0.3	0.8635	0.4637
0.3	0.35	0.9202	0.4832
0.2	0.4	0.9615	0.4952
0.1	0.45	0.9881	0.5
0	0.5	1	0.4962
-0.1	0.55	0.9971	0.4846
-0.2	0.6	0.9786	0.4653
-0.3	0.65	0.9434	0.4383
-0.4	0.7	0.8892	0.4035
-0.5	0.75	0.8121	0.3612
-0.6	0.8	0.7027	0.311
-0.7	0.85	0.5425	0.2532
-0.8	0.9	0.3586	0.1877
-0.9	0.95	0.1713	0.1143
-0.95	0.975	0.0823	0.0748
-1	1	0	0.0333

A5) UDF for ANSYS Fluent

```
/*******************************************************************
*
   UDF for specifying radial velocity profile
 ******************************************************************
*/

#include "udf.h"

DEFINE_PROFILE(x_velocity,t,i)
{
 real x[ND_ND];  /* this will hold the position vector */
 real y;
 real z;
 face_t f;

 begin_f_loop(f,t)
{
    F_CENTROID(x,f,t);
    y = x[1];
    z = x[2];

if ( (y*y+z*z)>pow(0.1,2) && (y*y+z*z)<= pow(0.551,2) )
{
    F_PROFILE(f,t,i) = -1.09854;
}
else  if( (y*y+z*z)>pow(0.551,2) && (y*y+z*z)<=pow(0.826,2))
{
    F_PROFILE(f,t,i) = -1.09854;
}
else  if( (y*y+z*z) > pow(0.826,2) && (y*y+z*z)<=pow(1.102,2))
{
    F_PROFILE(f,t,i) = -1.09854;
}
else  if( (y*y+z*z)>pow(1.102,2) && (y*y+z*z)<=pow(1.377,2))
{
    F_PROFILE(f,t,i) = -1.2450;
}
else  if( (y*y+z*z)> pow(1.377,2) && (y*y+z*z)<=pow(1.653,2))
{
    F_PROFILE(f,t,i) = -2.1238;
}
else  if( (y*y+z*z)> pow(1.653,2) && (y*y+z*z)<=pow(1.928,2))
{
    F_PROFILE(f,t,i) = -2.929;
}
else  if( (y*y+z*z)> pow(1.928,2) && (y*y+z*z)<=pow(2.204,2))
{
    F_PROFILE(f,t,i) = -3.808;
```

```
        }
        else  if( (y*y+z*z)> pow(2.204,2) && (y*y+z*z)<=pow(2.479,2))
        {
            F_PROFILE(f,t,i) = -4.76;
        }
        else  if( (y*y+z*z)> pow(2.479,2) && (y*y+z*z)<=pow(2.755,2))
        {
            F_PROFILE(f,t,i) = -5.127;
        }
        else
        {
            F_PROFILE(f,t,i) = -7.324;
        }
         end_f_loop(f,t)
        }
}
```

A6) MATLAB CODES

1) RPM for maximum efficiency

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%            Hydrodynamic Characteristics of        %%%%%%%%%%%%%%%
%%%%%%%%%%                 Screw Propellers                  %%%%%%%%%%%%%%%
%%%%%%%%%%                                                   %%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                                                                          %
%                              July 2013                                   %
%                                                                          %
% Ibrahim MANAURE TRUJILLO                                                 %
%                                                                          %
%                                                                          %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clear all;
close all;
format short;
rho = 1025;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

J = 0.05:0.05:1.8;

filename = 'HydrodynamicCharacteristicsOfScrewPropellers.xlsx'; % excel file with coefficients
sheet = 2;

xlrange = 'A1:B3';
subsetA = xlsread(filename,sheet);

Z = subsetA(1,1);
EAR = subsetA(2,1);


xlrange = 'E1:AN504';
kt = xlsread(filename,sheet,xlrange);

for i = 1:12,
    for j = 1:36,
        Kt(i,j) = kt(i*42,j);
    end
end

sheet = 3;
xlrange = 'E1:AN600';
kq = xlsread(filename,sheet,xlrange);

for i = 1:12,
    for j = 1:36,
        Kq(i,j) = kq(i*50,j);
    end
end
```

```
sheet = 4;
EFFICIENCY = xlsread(filename,sheet);

for i = 1:12,
    for j = 1:36,
        n_o(i,j) = EFFICIENCY(i*3,j);
    end
end

n_o(n_o>=1) = NaN;


figure;
plot(J,Kt);
axis([0.05 2 0 1]);
xlabel('ADVANCE COEFF [J]');
ylabel('THRUST COEFF [Kt]');
text(0.2,0.87,['EAR = ' , num2str(EAR)]);
text(0.2,0.82,['Z = ',num2str(Z)])
grid on;

figure;
plot(J,Kq, '--');
axis([0.05 2 0 0.20]);
xlabel('ADVANCE COEFF [J]');
ylabel('TORQUE COEFF [Kq]');
text(0.2,0.19,['EAR = ' , num2str(EAR)]);
text(0.2,0.17,['Z = ',num2str(Z)])
grid on;

figure;
plot(J,n_o);
axis([0.05 2 0 1]);
xlabel('ADVANCE COEFF [J]');
ylabel('EFFICIENCY');
text(0.2,0.87,['EAR = ' , num2str(EAR)]);
text(0.2,0.82,['Z = ',num2str(Z)])
grid on;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

options.Resize='on';

prompt = {'Ballast draugth (m):','Thrust (kN):','Velocity of advance
(m/s)'};
dlg_title = 'Particulars for initial propeller design';
num_lines = 1;
def = {'0','0','0'};
answer = inputdlg(prompt,dlg_title,num_lines,def,options);


d = answer{1};                    %[m]    heavy ballast draugth
Thrust = answer{2};               %[kN]
Va = answer{3};                   %[m]    velocity of advance

d = str2num(d);
Thrust = str2num(Thrust);
Va = str2num(Va);
```

```
D = 0.65*d;

Ktnew =  ( (Thrust*1000) / ( rho * (Va^2) * (D^2) ) ) * (J.^2);

figure;
plot(J,Kt);
title('');
hold on;
plot(J,Ktnew , '-b.');
axis([0.05 2 0 0.7]);
xlabel('ADVANCE COEFFICIENT [J]');
ylabel('THRUST COEFFICIENT [Kt]');
text(1.65,0.87,['EAR = ' , num2str(EAR)]);
text(1.65,0.82,['Z = ',num2str(Z)])
h = legend('0.5','0.6','0.7','0.8','0.9','1.0','1.1','1.2','1.3','1.4');
v = get(h,'title');
set(v,'string','P/D');
grid on;
```

2) Diameter for maximum efficiency

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%            Hydrodynamic Characteristics of        %%%%%%%%%%%%%%%
%%%%%%%%%%                 Screw Propellers                  %%%%%%%%%%%%%%%
%%%%%%%%%%                                                   %%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                                                                          %
%                              July 2013                                   %
%                                                                          %
% Ibrahim MANAURE TRUJILLO                                                 %
%                                                                          %
%                                                                          %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clear all;
close all;
format short;
rho = 1025 ;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

J = 0.05:0.05:1.8;

filename  =  'HydrodynamicCharacteristicsOfScrewPropellers.xlsx';  %  excel
file with coefficients
sheet = 2;

xlrange = 'A1:B3';
subsetA = xlsread(filename,sheet);

Z = subsetA(1,1);
EAR = subsetA(2,1);

xlrange = 'E1:AN504';
kt = xlsread(filename,sheet,xlrange);

for i = 1:12,
    for j = 1:36,
        Kt(i,j) = kt(i*42,j);
    end
end

sheet = 3;
xlrange = 'E1:AN600';
kq = xlsread(filename,sheet,xlrange);

for i = 1:12,
    for j = 1:36,
        Kq(i,j) = kq(i*50,j);
    end
end

sheet = 4;
EFFICIENCY = xlsread(filename,sheet);
```

```
for i = 1:12,
    for j = 1:36,
        n_o(i,j) = EFFICIENCY(i*3,j);
    end
end

n_o(n_o>=1) = NaN;

plot(J,Kt);
title('Thrust coefficient');
hold on;
%plot(J,n_o);
xlabel('ADVANCE COEFF [J]');
ylabel('THRUST COEFF [Kt]');
axis([0 1.5 0 1]);
h = legend('0.5','0.6','0.7','0.8','0.9','1.0','1.1','1.2','1.3','1.4');
v = get(h,'title');
set(v,'string','P/D');
grid on;

figure;
plot(J,Kq,'--');
title('Torque coefficient');
xlabel('J');
ylabel('Kq');
axis([0 1.5 0 0.20]);
h = legend('0.5','0.6','0.7','0.8','0.9','1.0','1.1','1.2','1.3','1.4');
v = get(h,'title');
set(v,'string','P/D');
grid on;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

options.Resize='on';

prompt = {'Power delivered (kW):','Engine revolution rate (RPM):','Velocity
of advance (m/s):'};
dlg_title = 'Particulars for initial propeller design';
num_lines = 1;
def = {'0','0','0'};
answer = inputdlg(prompt,dlg_title,num_lines,def,options);

Pd = answer{1};   %[m]    delivered power to the propeller
n = answer{2};    %[rpm]
Va = answer{3};   %[m]    velocity of advance

Pd = str2num(Pd);
n = str2num(n);
Va = str2num(Va);

n = n/60;       %[rps]

Kq2 =  ( Pd *1000 * n^2 * J.^5 ) / ( 2*pi*rho * (Va^5) )  ;

figure;
plot(J,Kq);
title(' ');
hold on;
```

```
plot(J,Kq2, '-b.');
xlabel('ADVANCE COEFFICIENT [J]');
ylabel('TORQUE COEFFICIENT [Kq]');
axis([0.05 1.5 0 0.20]);
h = legend('0.5','0.6','0.7','0.8','0.9','1.0','1.1','1.2','1.3','1.4');
v = get(h,'title');
set(v,'string','P/D');
grid on;
```

3) 2D geometry generation from lifting line results

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%         2D Geometry generation from lifting       %%%%%%%%%%%%%%%
%%%%%%%%%%                 line theory                       %%%%%%%%%%%%%%%
%%%%%%%%%%                                                   %%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                                                                          %
%                             November 2013                                %
%                                                                          %
% Ibrahim MANAURE TRUJILLO                                                 %
%                                                                          %
%                                                                          %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clear all;
close all;

format short;

rho = 1025;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Reading excel file with Data

filename = 'Data for creating 2D geometry of propeller.xlsx';
sheet = 1;
xlrange = 'B3:I14';
subsetA = xlsread(filename,sheet);
Data = xlsread(filename,sheet,xlrange);

for i = 1:12,
    r_R(i,1) = Data(i,1);
    thickness(i,1) = Data(i,2);
    c(i,1) = Data(i,3);
    f_m(i,1) = Data(i,4);
    pitch(i,1) = Data(i,5);
    alpha(i,1) = Data(i,6);
    beta(i,1) = Data(i,7);
    pitch_angle(i,1) = Data(i,8);
end

r = r_R*(5.51/2);

sheet = 2;
xlrange = 'B3:E30';
subsetA = xlsread(filename,sheet);
Data = xlsread(filename,sheet,xlrange);

for i = 1:28,
    epsilon(i,1) = Data(i,1);
    Fc(i,1) = Data(i,3);
    Ft(i,1) = Data(i,4);
end

% Radial distribution of pitch P(r)
```

```
% Radial distribution of chord length c(r)
% Radial distribution of maximum camber fm (r)
% type of camber distribution Fc (epsilon,r)
% type of thickness distribution Ft (epsilon,r)
% Radial distribution of maximum thickness e(r)
% Radial distribution os skew CS(r)
% Radial distribution of rake xR (r)
% hub shape

% j is for r/R
% i is for epsilon

for j=1:12,
    for i=1:28,
        Y_plus(i,j) = Ft(i,1)*thickness(j,1) + Fc(i,1)*f_m(j,1);
        Y_minus(i,j) = -Ft(i,1)*thickness(j,1) + Fc(i,1)*f_m(j,1);
    end
end
```

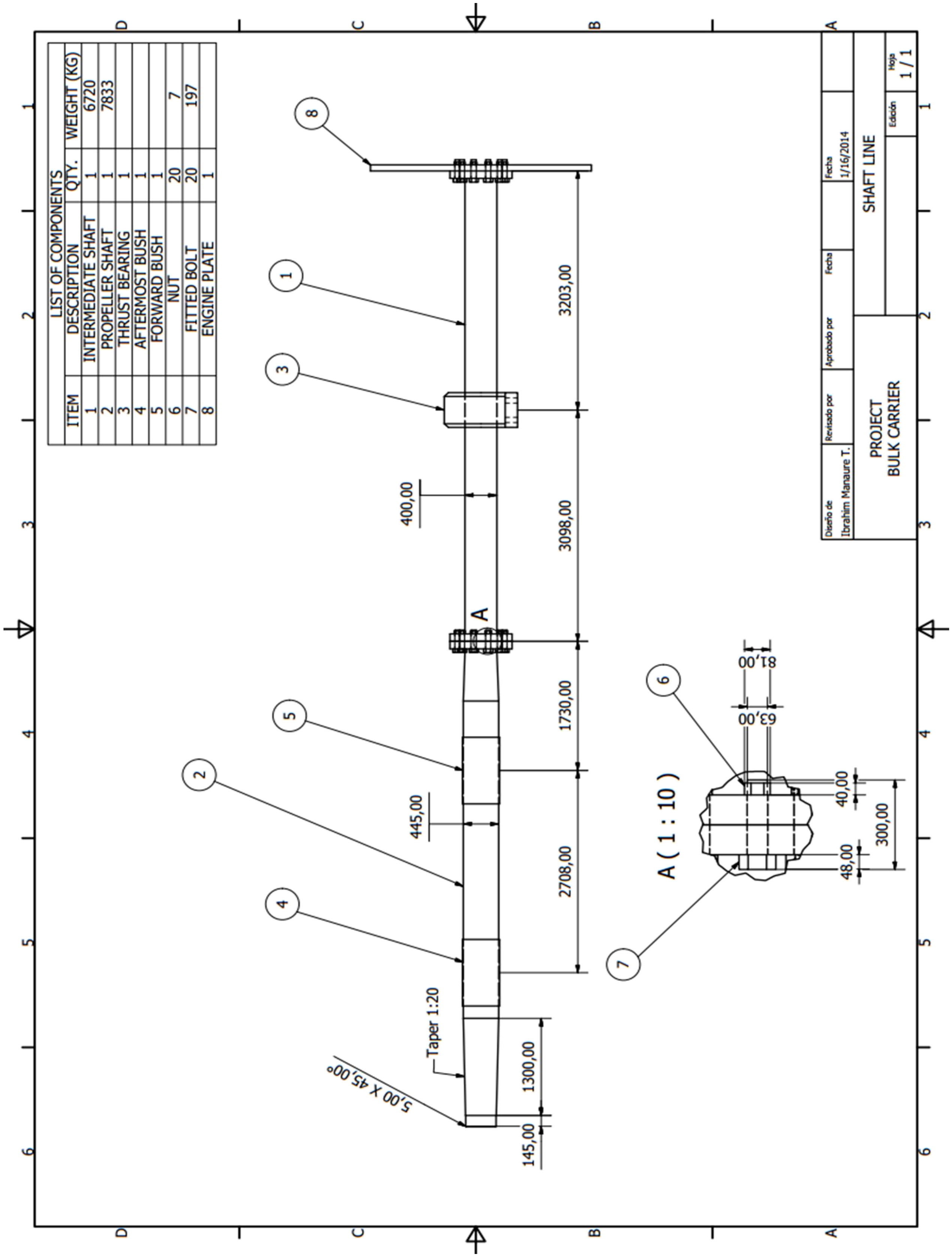
A6) Shipflow command file

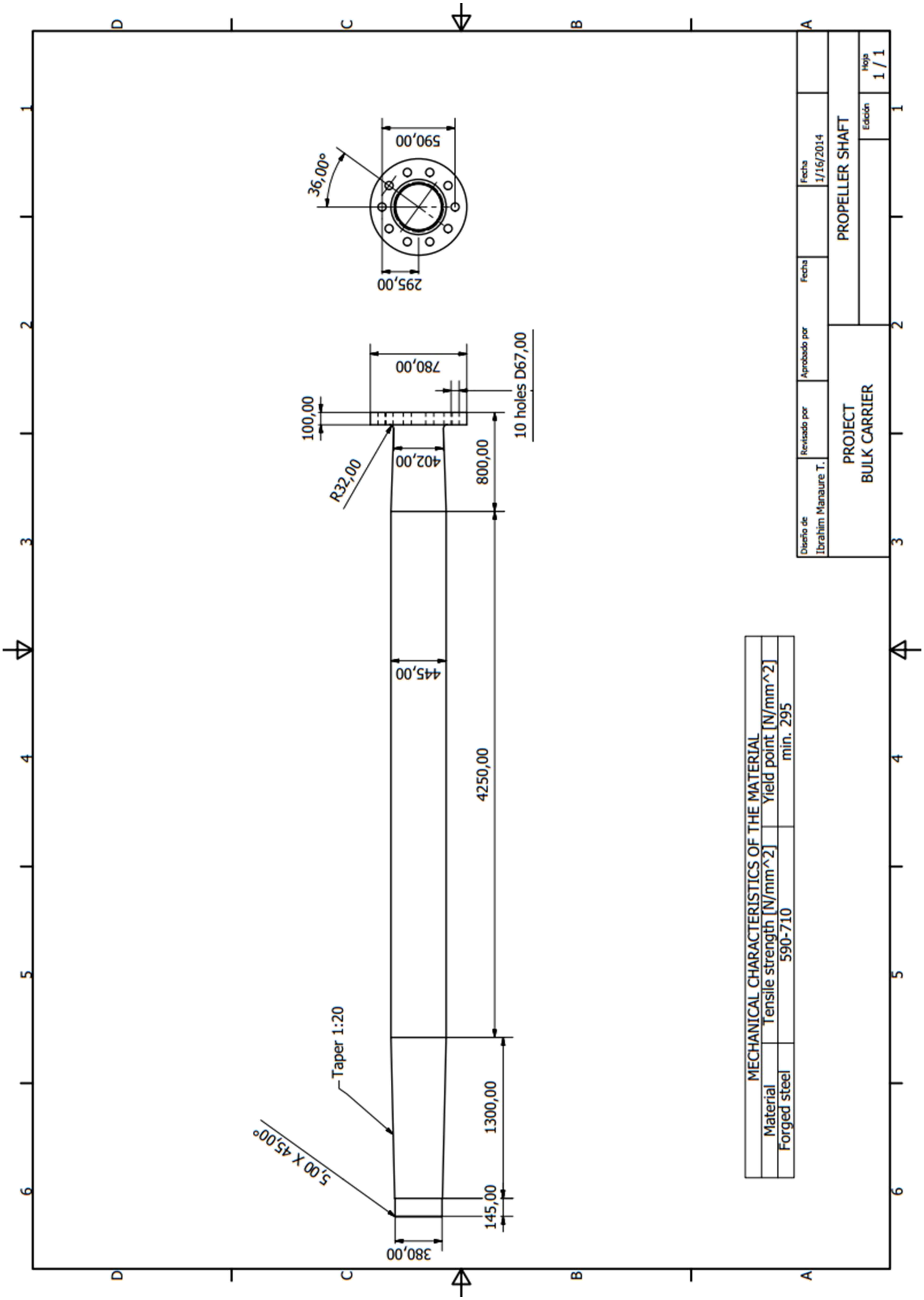
```
xflow
  titl ( titl="32000, propeller")
  prog ( xchap )
  hulltype ( POW )
  fluid (density = 1025.0, viscosity = 1.18e-6, gravity = 9.80665)
  vshi ( fn= [ 0.173810283 ], rn= [ 1068033898 ] )
 /  vshi ( VM_S=[7.4588] , reflen=188.0 )
/   offsetfile( file="off_ah", xaxdir=-1.0, ysign=1.0,
/              xori=70.54, zori=0.313, lpp=5.505 )
/************************propeller***************************/
    propeller (  id="prop", dpro=5.51, dhub=0.9918,xsh=0., zsh=0.,rotdir=1,
          nbla=4, numb=9,jv=0.62988,ear=0.6359,
          r_rt=[0.2,0.3,0.4,0.5,0.6,0.7,0.8,0.9,1.0],
          p_d=[0.6432,0.6811,0.6679,0.6555,0.6655,0.6723,0.6784,0.6785,0.6817],
          c_d=[0.265,0.294,0.319,0.34,0.356,0.362,0.353,0.307,0],
          t_d=[0.0422,0.0363,0.0307,0.0255,0.0207,0.01617,0.01185,0.00784,0.00399],
          camb=[0.073,0.0686,0.0468,0.0399,0.0358,0.0326,0.0305,0.0311,0.011]  )
/************************propeller***************************

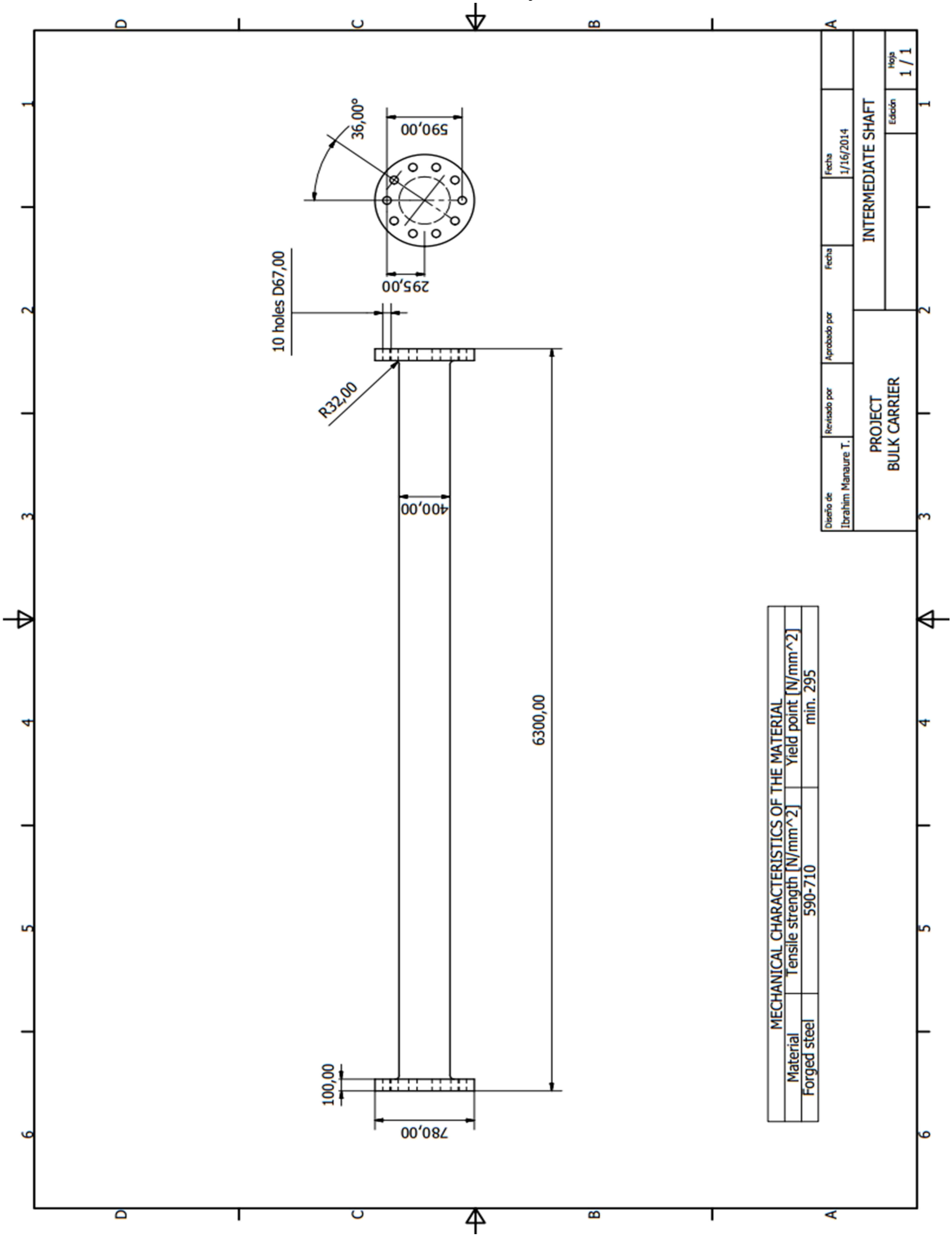
stretching( id="middlex", middle, s0=0.15, s1=0.8, ds0=0.35)
stretching( id="middlez", middle, s0=0.20, s1=0.8, ds0=0.15)
box ( low= [-2.0,-2.54,-2.54],high=[2.54, 2.54,.54],dime=[121,51,51],
str1="middlex", str2="middlez",str3="middlez",
bc11="INFLOW", bc12="OUTFLOW", bc21="SLIP",
bc22="SLIP",bc31="SLIP", bc32="SLIP")
symm( nosym )
end
```

```
xchap
parallel( nthread=8 )
control( start, maxiter=300 )
lline( id="prop",cf = 0.004, RELAX=0.15, ON)
POW( J=[0.1 , 0.2 , 0.3 , 0.4 , 0.4123 , 0.5 , 0.6 , 0.7 , 0.8 , 0.9 , 1] ,
outputfile="32000_pow.dat" , RN = 33627810.17 )
end
```

A7) SHAFTING DRAWINGS


LIST OF COMPONENTS
ITEM DESCRIPTION QTY. WEIGHT (KG)
1 INTERMEDIATE SHAFT 1 6720
2 PROPELLER SHAFT 1 7833
3 THRUST BEARING 1
4 AFTERMOST BUSH 1
5 FORWARD BUSH 1
6 NUT 20 7
7 FITTED BOLT 20 197
8 ENGINE PLATE 1
3203,00
3098,00
1730,00
2708,00
400,00
445,00
1300,00
145,00
Taper 1:20
5,00 X 45,00º
A
A (1 : 10)
81,00
63,00
40,00
300,00
48,00
Diseño de
Ibrahim Manaure T.
Revisado por
Aprobado por
Fecha
Fecha
1/16/2014
SHAFT LINE
PROJECT
BULK CARRIER
Edición
Hoja
1 / 1


MECHANICAL CHARACTERISTICS OF THE MATERIAL
Material
Forged steel
Tensile strength [N/mm^2]
590-710
Yield point [N/mm^2]
min. 295
PROPELLER SHAFT
PROJECT
BULK CARRIER
Diseño de
Ibrahim Manaure T.
Revisado por
Aprobado por
Fecha
1/16/2014
Edición
Hoja
1 / 1
590,00
295,00
36,00°
780,00
100,00
10 holes D67,00
R32,00
402,00
800,00
445,00
4250,00
Taper 1:20
1300,00
5,00 X 45,00°
145,00
380,00


36,00°
590,00
295,00
10 holes D67,00
R32,00
400,00
6300,00
100,00
780,00
MECHANICAL CHARACTERISTICS OF THE MATERIAL
Material
Forged steel
Tensile strength [N/mm^2]
590-710
Yield point [N/mm^2]
min. 295
Diseño de
Ibrahim Manaure T.
Revisado por
Aprobado por
Fecha
Fecha
1/16/2014
PROJECT
BULK CARRIER
INTERMEDIATE SHAFT
Edición
Hoja
1 / 1