Advanced Propulsion System
GEM 423E

Week 5: Propeller Design Overview

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Propeller Design

Propeller Design

- The propeller and its design process is an integrated entity.
- The completed propeller depends for its success on the satisfactory integration of several scientific disciplines.
- These are hydrodynamics, stress analysis, metallurgy, and manufacturing technology with supportive inputs from mathematics, dynamics, and thermodynamics.

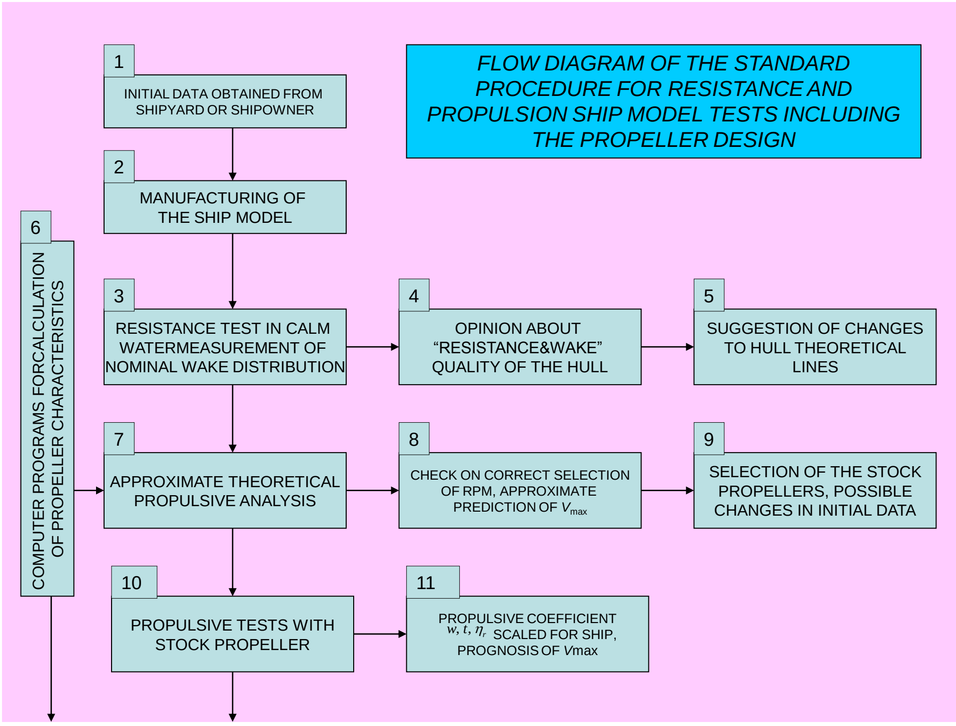
- The designer should produce an optimal design: optimal in the sense of satisfying the various constraint.
- In propeller technology, there is no single correct solution to a particular propulsion problem.

- It must be remembered that in general a propeller can only be designed for a single design point which involves a unique specification of a power, rotational speed and a mean radial wake field.
- The CP is the exception of this rule when it would be a normal to consider two or more design point.
- Although there is a unique design point in general the propeller operates in a variable circumferential wake field and may be required to work at off-design points sea trial condition.

A General Outline of the propeller design process

A General Outline of the propeller design process

- Block 1 of the diagram describes the starting point of the whole process.
- The initial data is supplied to the hydrodynamic laboratory by the shipyard of the ship owner. Normally these data consists of:
  - Theoretical lines of ship
  - Initial selection of the ship engine (i.e.. *RPM*, P_D)
  - Initial selection of the propeller diameter and number of blades (i.e.. *D*, *Z*)
- The selection is not dictated by purely theoretical optimum criteria.
- Initial selection of *D* and *Z* is a consequence of chosen hull lines and engine (e.g. Resonance vibration)


FLOW DIAGRAM OF THE STANDARD PROCEDURE FOR RESISTANCE AND PROPULSION SHIP MODEL TESTS INCLUDING THE PROPELLER DESIGN
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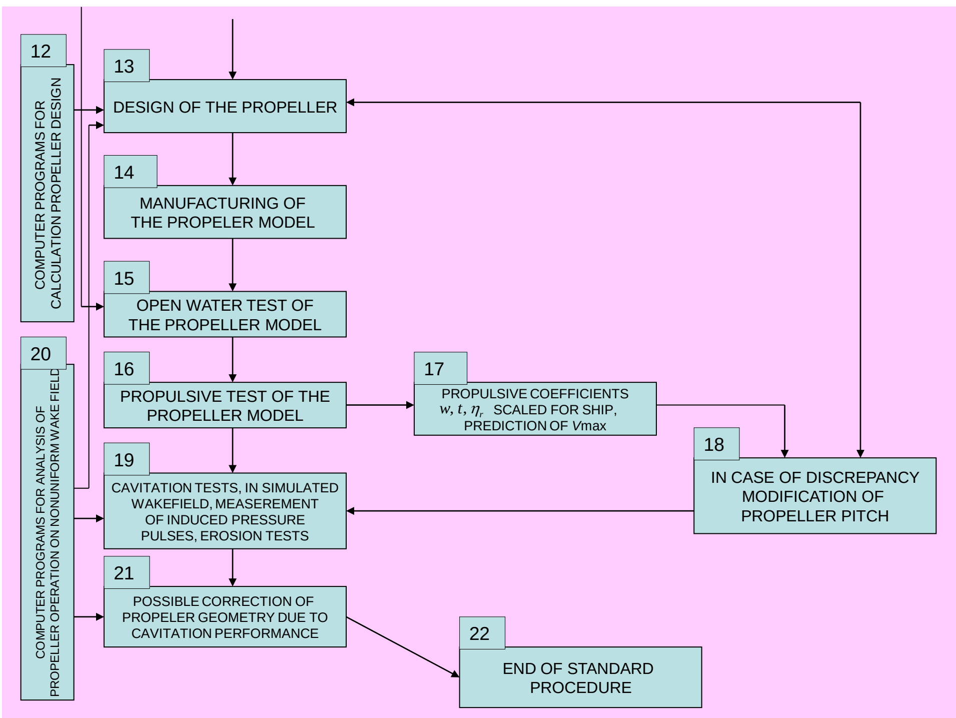
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END OF STANDARD PROCEDURE

- In block 2 the lab manufactures the ship hull model
- In block 3 the model is used for resistance measurement in calm water and measurement of the distribution of nominal velocity field at the location of the propeller.
- In Block 4 the opinion about the “resistance quality” and “wake distribution” of the shipyard design of the hull is formulated. If the lab feels that the resistance of the hull can be significantly reduced, the wake field at the propeller location can be made remarkably more uniform, then the proper modifications of the ship hull are suggested (block 5)

- In block 7 the approximate theoretical propulsive analysis of the ship is performed. In this analysis the resistance of the ship is taken from block 3. Propulsive coefficients are determined by approximate statistical methods and the data from systematic propeller series (e.g. Wageningen B) are employed.
- As a result of this analysis the correctness of D and RPM is verified and the first approximate prediction for the ship maximum speed “V_{max}” is done.
- At this stage, the analytical method for calculation of propeller hydrodynamic characteristics (block 6) is often used.

- As a result of blocks 7 and 8 a proper stock propeller is selected for the self-propulsion tests with the ship model.
- The stock propeller is a propeller model which has been already manufactured and tested before and most closely corresponds to the requirements of this particular ship design.
- If necessary, some changes are introduced to the main design parameters of the propeller (D, RPM, Z) on this occasion (block 9).
- The self-propulsion tests with the ship model equipped with the stock propeller are performed in the towing tank (block 10).

- As a result of the comparison of data from these tests with the known open water diagram of the stock propeller, the propulsive coefficients $w_t, t \text{ and } \eta_r$ are determined in block 11.
- They are normally scaled for ship's scale.
- The new more accurate prediction for V_{max} is performed.
- On the basis of the up to date accumulated information information the proper design of the propeller may be evaluated in block 13.
- The design calculations are based on the quasi-effective inflow velocity field (block 3), transformed in such a way that its mean value is equal to "w_t" from block 11.
- The final selection of "D" and "Z" is made here.

- The design calculations are performed by using the suitable computer program based on lifting line, or lifting surface theory (block 12).
- The initial design of the propeller is checked by the program for analysis of propeller operation in non-uniform inflow velocity field (i.e. wake) (block 20).
- The refined propeller model is manufactured in block 14 and the open water tests of it are repeated in block 16. From these tests the propulsive coefficients, $w_t, t \text{ and } \eta_r$, are obtained again, and scaled as before. More accurate prediction of the ship's maximum speed V_{max} is done (block 17).
- When a meaningful discrepancy is discovered between the values of the QPC from block 11 and block 17, an appropriate correction to the propeller pitch must be introduced.

Selection of the input data for the propeller design

Selection of the input data for the propeller design

- In this part, the important geometrical parameters of propellers, which are not directly calculated in the design procedures, are introduced.
- The criteria for selection of D, RPM, Rake&Skew and type of blade sections are discussed.

Propeller diameter

- There is always an upper limit for the propeller diameter determined by the ship hull theoretical lines and the requirement for keeping minimum clearances between the blade tips and hull surface recommended by the Classification Societies.
- These clearances are important for keeping the propeller induced pressure pulses within acceptable limits.
- However, the value of the optimum diameter should be evaluated in every case and applied if possible.
- If the optimum diameter is larger than the maximum diameter, the latter must be selected and the corresponding optimum revolutions of the shaft should be evaluated.

- In assessing the optimum diameter of a propeller which belongs to one of the systematic series, the appropriate diagrams may be employed.

$$\sqrt{\frac{K_T}{J^4}} = \sqrt{\frac{T\,n^4 D^4}{\rho n^2 D^4 V_A^4}} = \frac{n}{V_A^2}\sqrt{\frac{T}{\rho}}$$

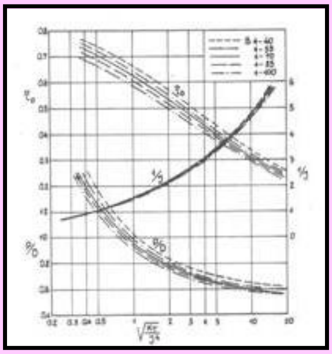
$where: T - Thrust$

$n - RPS$

$D - Diameter$

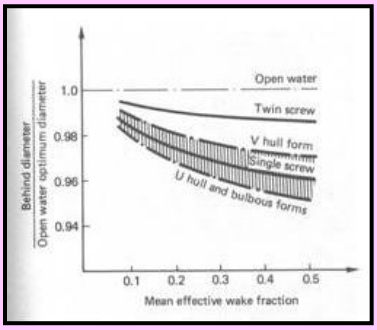
$V_A - Advance\,Velocity\,of\,prop.$

$\rho - density\,of\,water$



- For given values of $\sqrt{K_T/J^4}$, the value *1/J* is read off the diagram for a specified expanded area ratio and the optimum diameter may be easily evaluated.
- Apart from that the estimates of propeller efficiency η_0 and propeller pitch coefficient *P/D* may be obtained.
- One should remember that they are strictly valid for *open water propellers*.

- For an actual propeller working behind a ship the diameter needs to be reduced from the optimum value predicted from the standard series data, and traditionally this was done by reducing the optimum diameter by 5% and 3%, for single and twin screw vessels respectively.



- Another way of the determination of diameter is to use power coefficient which is:

$$B_p = \frac{P_D N}{V_a^{2.5}}$$

P_D : *Delivered power in British Horse Power*

N : *RPM*

V_a : *advance velocity in knots*

$$\delta_{opt} = 100\left[\frac{B_P^3}{\left(155.3 + 75.11\, B_P^{0.5} - 36.76\, B_P\right)}\right]^{0.2} \times \left[0.9365 + \frac{1.49}{Z} - \left(\frac{2.101}{Z} - 0.1478\right)^2 \times \frac{A_E}{A_0}\right]$$

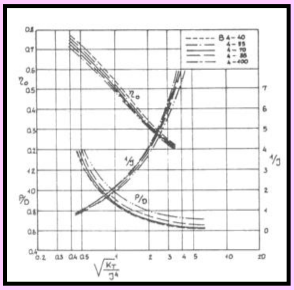
$$D_{opt} = \frac{\delta_{opt} V_a}{N} \quad (feet)$$

Propeller Number of Revolutions - RPM

- Analogically to the propeller optimum diameter, similar diagrams for the optimum number of propeller revolutions may be developed on the basis of systematic tests with series of propeller models.

$$\sqrt{\frac{K_T}{J^2}} = \sqrt{\frac{T\,n^4 D^2}{\rho n^2 D^2 V_A^4}} = \frac{1}{V_A}\sqrt{\frac{T}{\rho}}$$

- Similarly, for the given value of, $\sqrt{K_T/J^2}$ the value $1/J$ is read off the diagram for a specified expanded area ratio and the optimum number of revs is calculated.



- In order to avoid surprises one should realize that the diagrams presented do not represent the same optimum condition.
- When selecting "*D*" and "*n*" one should be aware of the danger of cavitation, which increases with increasing the blade tip velocity.
- In order to reduce the risk of heavy cavitation, the simple "rule of thumb" may be applied which requires that the tip speed V_{tip} should be:

$$V_{tip} \approx \pi D n < 30\, m/\text{sec.}$$

Rake

- Moderate raking of the propeller blade does not influence directly its hydrodynamic characteristics to any meaningful extent.
- Rake is applied to accommodate the propeller properly at the ship stern and keep the recommended clearances between the blades and the hull.
- Increase in rake results in increase of stress in the blades due to the inertia induced bending moments.

- Raked propeller have thicker blades than corresponding unraked propeller.
- This may also require increase in blade area in order to avoid cavitation in the design condition.
- The raked propellers have increased drag and slightly reduced efficiency in comparison to their unraked counterparts.

The figure right shows the typical placement of rudders and propellers for commercial workboats.

These figures are suitable for both single and twin-screw vessels.

Tip Clearance

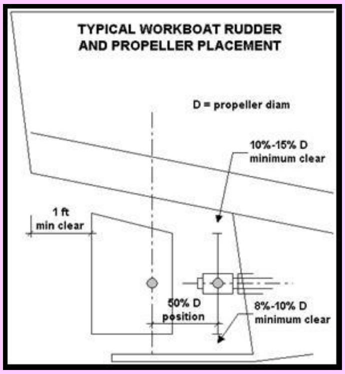
The figures shown represent the absolute min. Figures. Additional clearances –up to twice as much as the min figure – is better and recommended. Twin-screw vessels can typically get by with a bit less clearance than single screw vessels.

Rudder size

$$\text{Projected Area of Rudder} \approx 0.035\left(L_{wl} \times T\right)$$

Additional Comments

Remember to plan for the removal of the propeller and shafting. The space from the end of the shaft to the rudder must allow enough clearance for the hub of the propeller as it is removed or put in place. Also, it is common to offset the shaft to the side of the rudder, so that the shaft may be withdrawn without having to remove the rudder.



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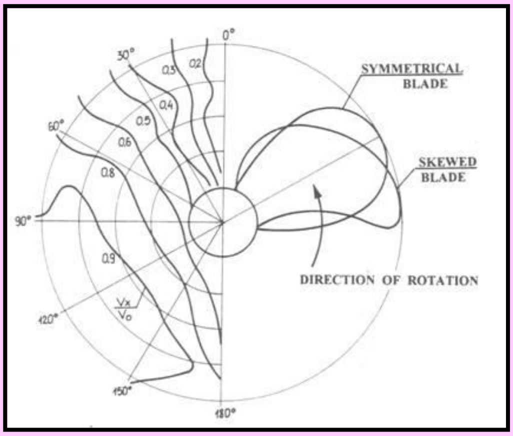
Skewback

The main purpose of applying skewback is to reduce the amplitudes of fluctuating bearing forces generated by the propeller, to reduce the amplitudes of pressure pulses induced in the surrounding space and to minimize the unsteady cavitation phenomena.

- Application of skewback to the propeller blades requires appropriate changes in other geometrical parameters of the propeller.
- The highly skewed propeller requires higher mean lines, camber and higher angle of attack of blade section in the outer section of blades than the corresponding propeller with symmetrical outline in order to realize the same desired loading distribution.

- The principal of the favourable effect of skewback is explained in the figure given below.



- When the symmetrical blade is turning, the blade sections at all radii enter the region of retarded flow simultaneously.
- Consequently, the loading of all blade sections increases at the same instant of time, thus giving sharp rise in propeller thrust and torque.
- In highly skewed blade this becomes more gradually.

Number of blade

- Increase in the number of blades causes reduction of the amplitude of fluctuating shaft forces and increase in their frequency.
- The same is true for pressure pulses induced by the propeller on the hull plating.
- The efficiency of the propeller drops with the increasing number of blades.
- The cost of manufacturing the propeller grows with increasing the number of blades.
- The practical choice is in most cases limited to 2 - 7 blades.

Direction of rotation

- From the propeller efficiency point of view, if the rotation exist in the wake field of a twin screw ship, due to the flow around ship at the propeller disc can lead to gain in propeller efficiency when the direction of rotation of the propeller is opposite to the direction of rotation in the wake field.

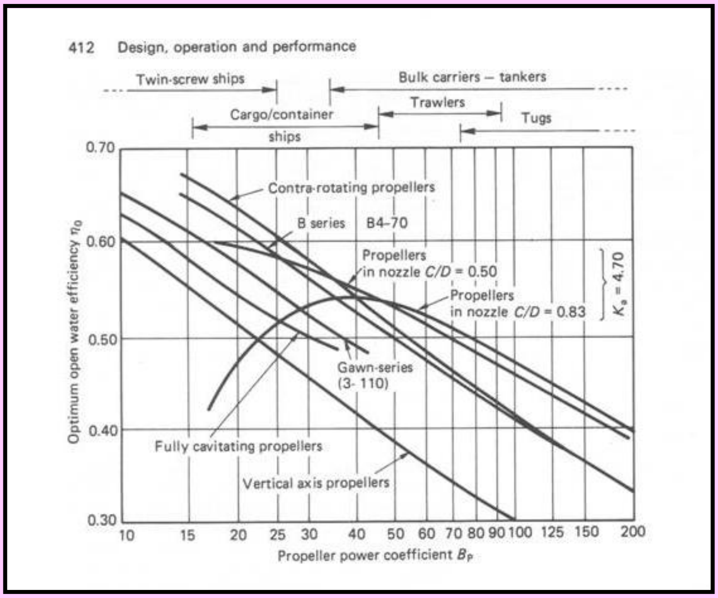
Blade section profile

- The brief text presented below refers to the blade sections suitable for design of non-cavitating or partially cavitating propellers.
- The proper selection of these should result from an optimum compromise between requirements of maximum profile efficiency and the best possible cavitation properties.
- NACA65 or NACA a=0.8 mean lines may be preferred because of their leading edge curvature.

The choice of the propeller type

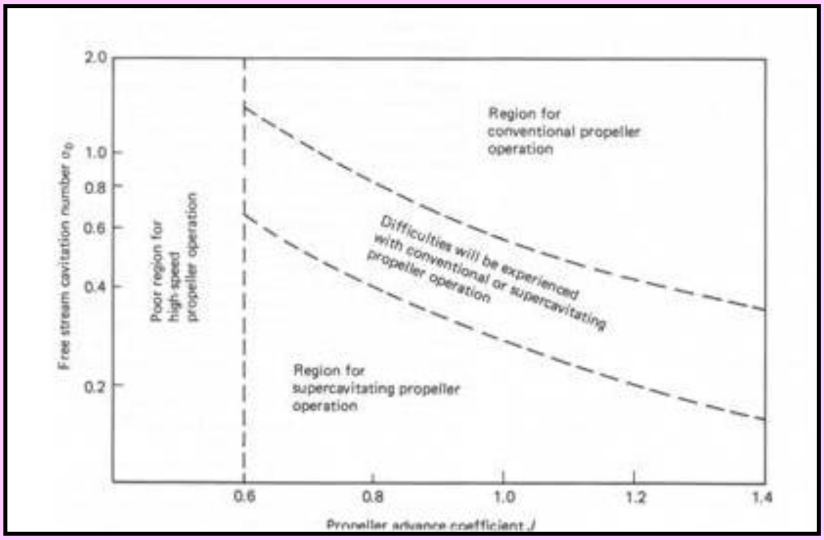
- The choice of propeller type for a particular propulsion application can be result of the consideration of any number of factors (the pursuit of max. efficiency, noise reduction, ease of manoeuvrability, cost of installation, ...).
- In terms of optimum open water efficiency van Manen (*) develop a comparison for a variety of propeller forms

- (*) Manen, J.D., van. The choice of the propeller, *Marine Technology*, April, 1966.



- In cases where cavitation is a dominant factor in the propeller design such as in high-speed craft, Tachmindji (*) *at al*. Developed a useful basic design diagram to determine the applicability of different propeller types with respect to cavitating conditions of these types of craft.

- (*) Tachmindji , A.J., Morgan, W.B., Miller, M.L., Hecher, R. The design and Performance of Supercavitating Propellers, DTMB Rep. C-807, February, 1957.



The propeller design basis

- The term '***propeller design basis***' refers to the power, rotational speed and ship speed that are chosen to act as the basis for the design of the principal propeller geometric features.
- The selection of the design basis starts with a consideration of the mission profile for the vessel.
- Each vessel has a characteristic mission profile which is determined by the owner to meet the commercial needs.

- Figure right shows three examples relating to a containership, a Ro/Ro, and a warship.
- The wide divergence in the form of these curves amply illustrates that the design basis for a particular vessel must be chosen with care such that the propeller will give the best overall performance in the areas of operation required.

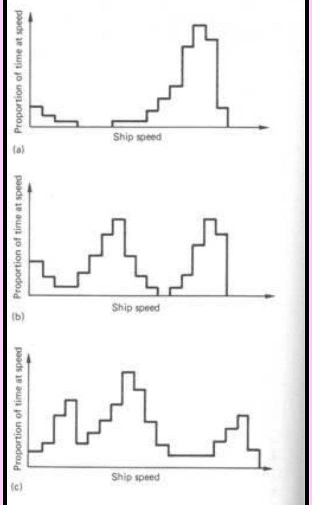
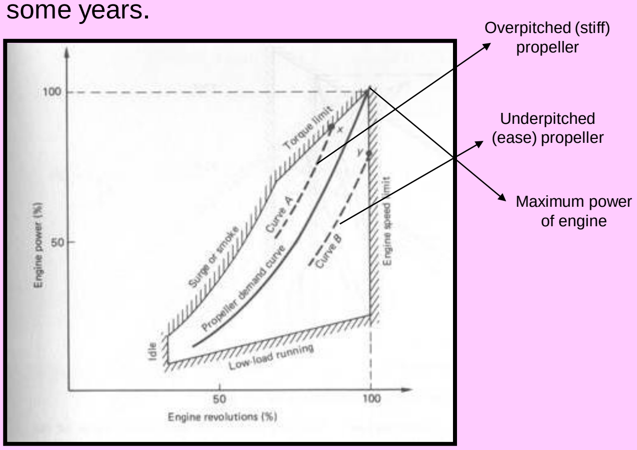


Figure 21.6 Examples of ship mission profiles: (a) container ship; (b) Ro/Ro passenger ferry; (c) warship

- In addition to satisfying the mission profile requirements it is also necessary that the propeller and engine characteristics match, not only when the vessel is new but also after the vessel has been in service for some years.



- If the pitch of the propeller has been selected incorrectly (curves A and B), the maximum power of engine will not be realized.

The propeller design with series charts

Types of Design Problems

- **Preliminary design:** Resistance and service speed is known, determine required engine power - $\mathbf{P_s}$ and propeller diameter - **D** or speed of rotation - **N**.
- With given P_E/R_T - V_S and D; determine - $\mathbf{P_s}$ optimum speed of rotation – **N** and efficiency of propeller.
- With given P_E/R_T - V_S and N; determine - $\mathbf{P_s}$ optimum diameter – **D** and efficiency of propeller.
- Main purpose: Determine main parameters of main engine.

Final design

- Ship resistance, engine power and speed of rotation known, design a propeller to best fit to hull and main engine i.e. to achieve maximum service speed and to make propeller excited vibration and noise levels as low as possible.

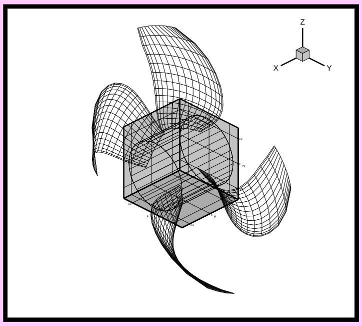
Design Methods-1

- **Design with series charts**: Interpolation for a propeller based on charts giving the results of open water tests on a systematic series of model propellers, such as B-Series, Gawn Series, AU/MAU Series.
- Simple, rapid reliable
- Limited by the propeller series used
- Possible cause of vibration and noise due to lack of consideration on wake non-uniformity

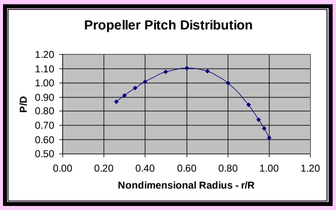
Design Methods-2

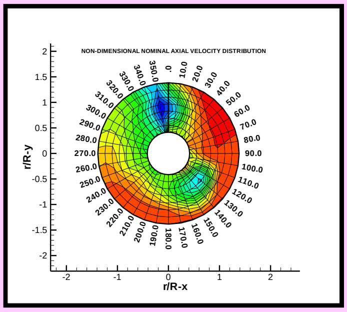
- **Design with circulation theory**: Lifting line method + performance of blade sections.
- Lifting surface methods
- Detailed design with distribution of camber and pitch determined to best fit with circumferentially averaged wake
- Flexibility on selection of blade outlines (skew and rake)
- Desirable if propeller is heavily loaded and liable to cavitation or has to work in a very uneven wake pattern.

Design Methods-3



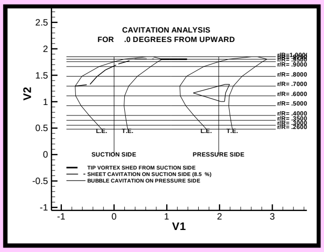
Lifting Surface Design – Wake adapted propeller

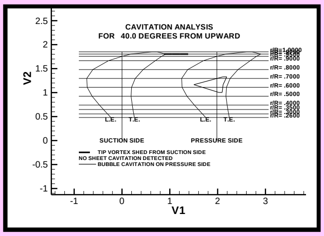


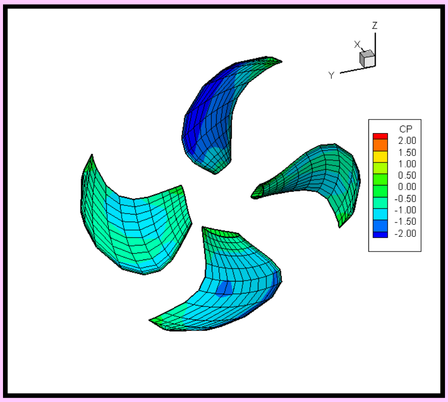


Optimal pitch distribution is obtained for proper wake

Design Methods-4





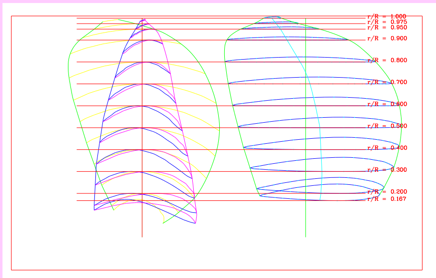


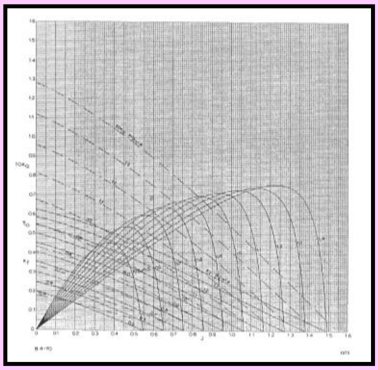
Cavitation performace can be predicted

Design Charts – Open Water Curves

- **Types of Charts**: Open water performance data. i.e. – K_t-K_q-J-η_0 curves

Opeb Water Diagrams of B 4.70 Propeller Series





Design Charts – Selection Options

- **Known Thrust and Diameter**: If thrust produced by propeller and diameter is known

$$\frac{K_T}{J^2} = \frac{T}{\rho V^2 D^2}$$

- **Known Power and Rotation Rate**: If power to be absorbed by propeller and rotation rate is known

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

Design Charts – Selection Options

- Program "PropCalc" can performed all options

	PropCalc Program Options
1	Optimum Rotation Rate for a Given Diameter
2	Optimum Diameter for a Given Rotation Rate
3	Optimum Propeller for Given Power and Rotation Rate
4	Maximum Bollard Pull
5	Open Water Performance Analysis
6	Propeller Performance Analysis Including Viscous Scale Effects According to the ITTC78 Recommendations
7	Calculation of Non-optimum Propeller Performance Analysis Including Viscous Scale Effects According to the ITTC78 Recommendations
8	Calculation of a Certain Propeller Performance Analysis Including Viscous Scale Effects According to the ITTC78 Recommendations

Design Charts – Usual Way

- Usual Way to obtain correct match with propeller and main engine; Steps
- **<1> Select Option 1:** Obtain n, delivered power P_D; make decision about main engine. (Propeller thrust = Ship resistance including thrust deduction at service speed
- **<2> Select Option 3:** For specific main engine (n may be different than that of obtained in step <1>; redefine propeller characteristics. (Required propulsive power = engine power at design speed of rotation)
- **<3> Select Option 8:** Final decision is made together with the decision of blade area ratio (cavitation control).

Design Charts – Finalization

- Determine propulsion factors – propulsion analysis

V_s (knots)	P_e (kWs)	w_t	t	η_H	η_0	η_r	η_d	P_d (kWs)	P_{bmin} (kWs)
6.00	217	0.287	0.232	1.077	0.550	1.018	0.603	360	375
7.00	348	0.287	0.232	1.077	0.548	1.018	0.601	579	604
8.00	525	0.287	0.232	1.077	0.546	1.018	0.598	877	914
9.00	748	0.286	0.231	1.077	0.547	1.018	0.600	1248	1300
10.00	1027	0.285	0.230	1.077	0.547	1.018	0.600	1713	1784
11.00	1372	0.285	0.230	1.077	0.547	1.018	0.600	2288	2384
12.00	1786	0.285	0.231	1.075	0.546	1.018	0.598	2989	3113
13.00	2299	0.285	0.232	1.073	0.544	1.018	0.594	3867	4028
13.50	**2590**	**0.285**	**0.237**	**1.067**	**0.542**	**1.018**	**0.589**	**4399**	**4582**
14.00	2889	0.284	0.240	1.061	0.542	1.018	0.585	4936	5141
14.50	3212	0.284	0.252	1.045	0.539	1.018	0.573	5602	5835
15.00	3593	0.284	0.255	1.040	0.537	1.018	0.569	6318	6581
15.50	4076	0.284	0.263	1.029	0.531	1.018	0.556	7327	7632
16.00	4731	0.284	0.270	1.020	0.521	1.018	0.541	8748	9112
16.30	5259	0.284	0.270	1.020	0.513	1.018	0.533	9876	10287

Design Charts – Finalization 2

- Propeller strength calculation
- Calculation of weight and moment of inertia (If program “PropGeom” has been used they were already obtained)
- Calculation Propeller Performance under Bollard Condition
- Calculate nautical characteristics
- Make propeller drawing

Propeller Strength Calculation

- Propeller strength calculation is performed according to the rules of classification society rules.
- For example Chine Classification Society (CCS)

Propeller Weight and Moment of Inertia

- Example output of program "PropGeom"

```
-- KANAT AGIRLIGININ HESABI --
------------------------------
 i    r(i)      Ax(i)      m(i)
      (cm)      (cm2)      (kg)
------------------------------
 1   10.00     73.399      ---
 2   15.00     75.732      3.21
 3   20.00     72.885      3.20
 4   25.00     65.373      2.97
 5   30.00     54.748      2.58
 6   35.00     42.325      2.09
 7   40.00     28.812      1.53
 8   45.00     14.917       .94
 9   47.50      6.784       .23
10   48.75      3.006       .05
11   50.00      1.045       .02
------------------------------
```

```
       TEK KANADA AIT DEGERLER
-----------------------------------------
m      =     16.9 kg (    16.8 kg basit toplam)
Iox    =    .05 kg*m2 (saft eksenine gore)
V      =    1965.   cm3  (pervane hacmi)
Zc     =    .24 m (saft eksenine gore)
rho_m = 8600.0 kg/m3 (malzeme yogunlugu)
```

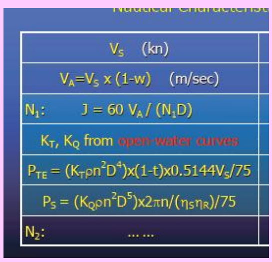
Propeller Performance under Bollard Condition

- K_{T0} and K_{Q0} values at J=0 are read off open water curve of designed propeller
- Max. Continious power P_D is then taken as Bollard Power. Therefore Torque - Q is calculated for that power.
- Thrust under Bollard Condition
- Speed of rotation under Bollard condition

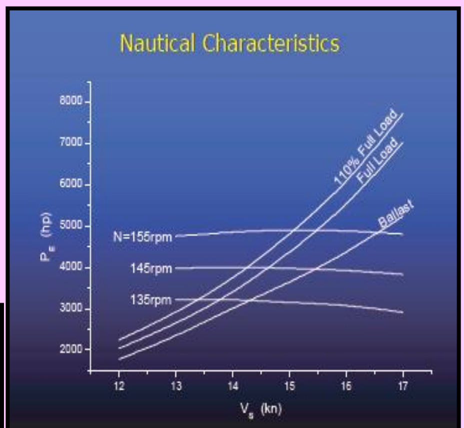
$$T = \frac{K_{T0}}{K_{Q0}} \frac{Q}{D}$$

$$N = 60\sqrt{\frac{T}{\rho D^4 K_{T0}}}$$

Nautical Characteristics



V_S (kn)
$V_A = V_S$ x (1-w) (m/sec)
N_1: $J = 60\ V_A / (N_1 D)$
K_T, K_Q from open-water curves
$P_{TE} = (K_T \rho n^2 D^4)$x(1-t)x0.5144$V_S$/75
$P_S = (K_Q \rho n^2 D^5)$x2πn/($\eta_S \eta_R$)/75
N_2: ……



Effective powers are calculated for different loading conditions. Thrust and absorbed power of propeller with underload and overload conditions (i.e. 110-0.90% MCR) are calculated considering propulsive factors and losses. Curves are then plotted on th same sgraph. Therefore speed achieved can be observed from the graph