YILDIZ TEKNİK ÜNİVERSİTESİ
GEMİ İNŞAATI VE DENİZCİLİK FAKÜLTESİ
GEMİ İNŞAATI VE GEMİ MAKİNALARI MÜHENDİSLİĞİ

YÜKSEK LİSANS ÖDEVİ

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**PROPULSORS FOR HIGH SPEED CRAFT**

**REVIEW**

Speed is the most important factor dominating the power requirement and selection of propulsor type.

Following is an interesting comparison of two different types of vessel:

<table>
<thead>
<tr>
<th>Oil Product Carrier</th>
<th>vs</th>
<th>Patrol Craft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Δ=37600 tonnes</td>
<td></td>
<td>Δ=72 tonnes</td>
</tr>
<tr>
<td>V=15 knots</td>
<td></td>
<td>V=26 knots</td>
</tr>
<tr>
<td>P_B=7640 kw</td>
<td></td>
<td>P_B=2030 kw</td>
</tr>
<tr>
<td>P_B/Δ=0.2 kw/tonnes</td>
<td></td>
<td>P_B/Δ=29 kw/tonnes</td>
</tr>
<tr>
<td>RPM=115</td>
<td></td>
<td>RPM=766</td>
</tr>
</tbody>
</table>

**PROPULSOR TYPES**

1. Transcavitating (or subcavitating) propellers
2. Supercavitating propellers
3. Surface-piercing propellers
4. Water jets

1. **Transcavitating Props:** These propellers operate at high speed, high thrust, and low immersion and hence they are bound to experience cavitation problems which dominate their design. In order to give immersion, “Inclined Shaft System” is used. This may make cavitation problems worse due to non-uniform flow effects on the propeller even with large propeller areas.

The soft inclination depends on the vessel size & speed, e.g.,

- Small pleasure crafts V<20 knots:
- Larger crafts Δ>20 m³, 25 < V < 40 knots:

For optimum efficiency & small vibrations, \( \varepsilon = 6 \) to 8 degrees

(Where 6 is the Total shaft inclination angle made with horizontal plane)
In some cases in order to reduce the draft, these propellers are arranged in semi-ducts or tunnel stern.

Transom inounted Z-drives with transcavitating propellers are applied at small pleasure crafts with outboard engines.

For Larger crafts Z-drive systems moonted at the bottom of the hull as “tractor” or “pusher” clarm higher propulsive efficiency than the conventional propulsar arrangement.

2. Supercavitating Propellers: Supercavitation is the satisfaciory performance with conventional propellers to quite high craft speect at low cavitation number such that all back of the propeller blades is covered by cavitation.
The use of supercavitating propellers show strong decline. They are not applied at commercial crofts, because modern propeller design allows to operate at speeds up to ...42 knots without considerable cavitation and erosion.

Supercavitating propellers are appropriate in speed region of 40-60 knots.

3. **Surface-piercing propellers**: They are increasingly used in recent years V>35 knots. Where they have higher propulsive efficiencies than subcavitating propellers. They don’t have an appendage drag and may have thrust vectoring capability which requires no rudder.

![Surface-piercing propeller](image)

They have been used mainly by offshore racing crafts (above 60 knots), leisure crafts etc.

4. **Water jet propulsion**: Water jet propulsion is no longer limited to special high speed crafts. Although they are recognised to be less efficient compare to conventional propellers, in particulars at low speed range, their efficiency has been improving. They have application to all high speed crafts, in particular for high speed catamarans. They have low noise, vibration and wash effects at banks.

![Water-jet](image)

The propellers in the pump may have fixed or controllable pitch.

See figure for approximate max’ efficiency envelopes of the above propeller types.
- At low speeds W/J are not efficient.

- According to the efficiency the best one is surface piercing props up to (%65-70) efficient.

**(CONVENTIONAL) TRANSCAVITATING PROPELLERS**

These propellers are commonly used on semi-displa-cement round bilgse hulls, planing hulls, catamarons, SWATH ships but also on SES’s and hydrofoil crafts.

They have fully wetted blade profiles on which the Local static pressure at any point remains well above the vapor pressure fot most operating conditions.

The selection of a proper propeller needs a careful consideration of the specific desing canations ana the factors affecting the propulsion such as Shaft Inclination, Cavitation, propeller-hull interaction, vibrations, power distribution, operational conditions etc. (An overall review of these effects can be found in WEGEMT-89 paper bye Muller Graf and the students are strongly recommended to read this reference)
**EFFECT OF SHAFT INCLINATION**

Inclination is necessary to provide the subcavitating propeller fully wetted condition and to reduce the risk of air suction or ventilation at all trim angles underway.

The inlined shaft affects resistance, running trim and propulsive qualities. The oblique flow is the main source of cavitation, vibration, thrust and torque fluctuations.

\[ \varepsilon, \text{ total shaft inclination angle} = \text{Shaft inclination to keel} + \text{Running trim} \]

The mean wake and wake fraction of high speed vehicles is very small although local wake variation which is the main cause of cavitation, could be very large due to shaft brackets, struts and inclined shaft.

The oblique inflow of the propeller causes a cyclic variation of the angle of attack at the propeller blade profiles causing the same effects which arise due to non-uniform wake distribution. However these effects can be more than the non-uniform wake case. The cyclic variation of the angle of attack is due to cyclic component of the tangential velocity \( V_a \sin \varepsilon \sin \theta \) as follow.
Depending upon angular position of blade (ie $\theta$), the tangential velocity varied between two extreme

So although we may have well designed section, we have the problem of fluctuating angle of attack.

Considering the angular speed under the effect of the fluctuating tangential velocity (ie $2\pi r + Va \sin\theta \sin\theta$) at root, $r$ is small but $Va \sin\theta$ can be large and towards the inner part of the blade cross-flow have dominant effect.

Correspondingly the effect will be smaller in proportion towards the tip. This leads to cavitation towards the root causing root erosion. We may also face cavitation and back cavitation.

Max thrust $\neq$ design thrust

Non-cavitating prop is more important!

Alternately due to the cross-flow effect which is a nightmare

Effect of Shaft Inclination & unsteadiness of cavitation influence the design such that:
1. As shown in the above figures for small variation of revs, propeller may not achieve the design thrust for cavitating propellers. (ie in circled region average thrust ≠ design thrust for the cavitating prop)

2. Erosion may occur. Blade surface erosion will be seen. However, this will not be as severe as Merchant ships since the cavitation develops behind the propeller. Root cavitation is the main danger and causes rapid erosion. To avoid use vanes, pressure relieving hole or injecting air at roots (ie AGOUTI propellers to provide air wash for the detrimental effects of exploding cavities)

3. The intensified cavitation phenomena contribute to propeller induced hull surface pressures. The larger pressure loadings aggravate the hull vibrations and the fatigue failure of the hull plating above the propeller.

4. Change in angle of attack due to shaft inclination will result in thrust and torque fluctuations.

**CONVENTION FOR PROPELLER INDUCED FORCES & MOMENTS**

Due to this feature the thrust and torque fluctuation, the thrust eccentricity, the blade and shaft bending moments as well as the bearing loads become larger.

5. The shaft inclination also cause reduction in thrust and unbalanced vertical force which effects trim.
POWERING PREDICTION & PROPELLER SIZE FOR CRAFT WITH INCLINED SHAFT

ALGORITHM

Assume total resistance $R$ (kN) at design speed $V_s$ (knots) is known.

Assume engine range & gear box ratio have been selected i.e propeller rate of rotation, $N$ (rpm) is known

If total shaft inclination is $E$
-For steady speeds

\[ R = (T \cos \varepsilon - F \sin \varepsilon) Np \]

Where Np: number of propeller (Note that thrust deduction fraction t is assumed negligible)

Say,

\[ F_n = kT \]

\[ R = (T \cos \varepsilon - kT \sin \varepsilon) Np \]

Required axial thrust per shaft

\[ T = \frac{R}{(\cos \varepsilon - k \sin \varepsilon) Np} \]

Axial advance velocity, \( V_a \)

\[ V_a = V \cos \varepsilon \]

(Note that fraction is assumed negligible)

Assume a value for \( k \) from available data bank estimate thrust power, \( P_T \)

\[ P_T = T \times 0.5148 \ V_a \ (\text{kW}) \]

Assume initial value of propeller efficiency \( \eta_0 \)

\[ \text{Delivered power, } P_D = \frac{P_T}{\eta_0} \]

\[ \text{Calculate } B_p = 1.158 \ \frac{N \ P_D}{V_a ^{2.5}} \]

Select appropriate \( B_p - \varepsilon \) diagram from available Design charts for high speed props and read-off \( \eta_0 \) at optimum efficiency line

- Compare with previous value and iterate until converge if necessary. At convergence read-off new.

\[ \eta_0, \ P/D \text{ and } S \]
Note that: In the above algorithm the Standard approach for propulsive efficiency calculation (i.e. $\eta_D = \eta_0 \eta_h \eta_r$) is not used and it is assumed that $\eta_D = \eta_0$ due to small interaction effect the propeller and the hull. Because of the greater distance between the propeller pressure field and parts of the hull in front of it, the change in flow around the afterbody is comparatively small and the above assumption can be justified for practical purposes.

**SPEED PREDICTION FOR GIVEN ENGINE AND CRAFT WITH INCLINED SHAFT**

**ALGORITHM**

- Assume Total drag $R_T$ vs Speed $V_s$ curve is available

- Assume Delivered power, $P_D$ and propeller rate of rotation, $N$ are known

  Then proceed as follows:

- If total shaft inclination is $\varepsilon$°

- For a range of speeds, $V_s$, on either side of anticipated speed calculate.

  Advancve velocity in direction of fwa motion i.e $V_a$

  $V_a = V_s (1 - w)$

  (Although wake fraction $w$ should be taken into account, because of its small value it is neglected for practical purposes)
- Advance velocity in axial direction (ie along shaft) $V_{ax}$

$$V_{ax} = V_a \cos \varepsilon$$

- Power coefficient $B_p$

$$B_p = \frac{N \rho D^3}{V_{ax}^5 \pi} \left\{ \begin{array}{ll} \text{rpm} & \\
\text{kW} & \\
\text{knots} & \end{array} \right.$$ 

- Select ($B_p - \delta$) diagram for appropriate $Z$, B.A.R $\sigma_v$ 

($\sigma_v$ is the cavitation number based on axial velocity)

- Calculate thrust $T$ for corresponding speeds from

$$P_T = P_{D, Y_0}$$

$$T = \frac{P_T}{V_{ax}}$$

- NETT driving force, $F_{netT}$, by taking into account thrust deduction fraction $t$ on a number of props $N_p$ is

$$FN = (T \cos \varepsilon - F_N \sin \varepsilon)(1 - t)N_p$$

(Note that although the thrust deduction, $t$ should be taken into account because of its small magnitude it can be neglected for practical purposes)

- Plot $F_{NETT}$ & $R_T$ Vs Vs and read off $V_{predicted}$ at the intersection point.

Some cases effect of $F_2 \sin t$ can be included $(1-t)$ term which can be considered as virtual thrust deduction.
TRANSCAVITATING PROPELLER DESIGN

Standard series data (with Bp-δ type representation or equivalent representation for the open water propulsive characteristics).

Is still the key element in designing these propellers. However, the effect of cavitation should be taken into account in the open water curves. Therefore, the classical series data developed in the model tanks are not suitable, and high-speed propeller series are usually derived in cavitation tunnels taking into account static pressure variations (i.e., varying ζ).

Furthermore, high-speed propellers are different than standard Merchant ship propellers. They have usually less blade numbers to reduce frictional resistance, large B.A.R to reduce thrust coefficients and, hence, reduce cavitation, wider blade tips, and segmental sections to improve cavitation characteristics, etc.

Limited amount of Series Data is available allowing the influence of cavitation on propeller design characteristics. Amongst them:

1- GAWN-BURRILL (or KCA) series
2- NEWTON-RADER series
3- OTHERS (by Russians & Bulgarians)

(G/B or ) KCA SERIES

This series is a complementary series to GAWN series. The KCA (King College-A) series comprise 3 bladed, wide tipped, segmental (or round back) section, uniform pitched 30 propellers, 06 mm radius (16”)

B.A.R = 0.5, 0.65, 0.80, 0.95; 1.10
P/D = 0.6, 0.80, 1.0, 1.2, 1.4, 1.6, 2.0

See following figure for blade details of KCA series.

This propeller series was tested at the Cavitation Tunnel at the University of Newcastle u/t. The range used gave a series of 6 cavitation number ? based on the free stream advance velocity as
Diameter = 16-00 ins.  B.L.r = .045  d/O = 0.20.
Number of Blades = 3 R.H.  B.A.R. = 0.80
Model Propeller Series. Parent Screw

<table>
<thead>
<tr>
<th>B.A.R.</th>
<th>0.50</th>
<th>0.65</th>
<th>0.80</th>
<th>0.95</th>
<th>1.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>E.R.</td>
<td>R=75</td>
<td>R=75</td>
<td>R=75</td>
<td>R=75</td>
<td>R=75</td>
</tr>
<tr>
<td>6:32</td>
<td>5:25</td>
<td>6:66</td>
<td>8:42</td>
<td>10:28</td>
<td>1:00</td>
</tr>
<tr>
<td>6:33</td>
<td>5:25</td>
<td>6:66</td>
<td>8:42</td>
<td>10:28</td>
<td>1:00</td>
</tr>
<tr>
<td>6:74</td>
<td>5:25</td>
<td>6:66</td>
<td>8:42</td>
<td>10:28</td>
<td>1:00</td>
</tr>
<tr>
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<td>10:28</td>
<td>1:00</td>
</tr>
</tbody>
</table>

FILLET RADIUSare REDUCED GÜADUALLY 10-02 AT LEADING AND TRAILING EDGES.

BLADE EDGE RADIUS = 0.25.
\[ \sigma_v = 6.3, 2.0, 1.5, 0.75 \text{ and } 0.5 \]

With \[ \sigma v = \frac{p_0 - p}{\frac{1}{2} \rho v^2} \]

(note that \( V \) is free stream velocity and \( \sigma_v = 6.3 \) corresponds Atmospheric pressure case)

The above data was published:

- First as \( K_T, K_a, \gamma_0 \) vs \( J \) by GAWN BURRIL in Trans RINA, Vol 99, 1957
- Re-analysed data were presented as \([Bp-\delta]\) charts by EMERSON SINCLAR in NECIES, Vol 94, 1978

As a consequence using this series it is possible to study the effects of the global cavitation performance of a proposed propeller design.

**Final Remarks on KCA SERIES**

As mentioned earlier, in order to assist in design studies using the KCA series, EMERSON & SINCLAR re-analysed the G/B data and have presented charts for the series both at non-cavitating and cavitating conditions, together with additional thrust and torque data for a B.A.R of 1.25 and P/D = 1.0

Despite a lack of data at very low \( J' \) values due to the experimental limitations of the N/University cavitation tunnel, the KCA series of propellers, when used in conjunction with the original GAWN series (GAWN, RINA 1953) provides an immeasurably valuable set of data upon which to base design studies of high-speed craft or naval crafts.

**NEWTON-RADER SERIES**

This series embraces 12, three-bladed high speed propellers. The extent of series as follows.

<table>
<thead>
<tr>
<th>B.A.R</th>
<th>P/D</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.48</td>
<td>1.05, 1.26, 1.67, 2.08</td>
</tr>
<tr>
<td>0.71</td>
<td>1.05, 1.25, 1.66, 2.06</td>
</tr>
<tr>
<td>0.95</td>
<td>1.04, 1.24, 1.65, 2.04</td>
</tr>
</tbody>
</table>

The parent model of the series had constant pitch ratio of 1.25 with a non-linear blade thickness distribution. The blade section form was based on the NACA a=1.0 mean line with a quasi-elliptic thickness form super imposed as shown in the following figure.

Each of the propellers was tested in a cavitation tunnel at 9 different \( \sigma_v \) values as:

\( \sigma_v = 0.25, 0.30, 0.40, 0.5, 0.60, 0.75, 1.0, 1.25 \text{ and } 5.5 \)
Two different $R_n$ applied during the tests to take into account the narrow-bladed and wide-bladed nature of the series.

The results of the series are presented largely in tabular forms by NEWTON & RADER in (Trans RINA Vol 103, 1961)

This series is of considerable importance for the design of propellers, usually for relatively small craft, where significant cavitation likely to be encountered.
EXAMPLE FOR TRANSCAVITATING PROPELLER DESIGN BY USING KCA (GAWN-BURRILL) DATA

INPUT DATA

Vessel type = Wall sided hovercraft
Delivered power , $P_D = 1104$ kw/shaft
Propeller speed , $N = 1193$ r.p.m
Advance velocity , $V_a = 35$ knots
Total shaft angle , $\epsilon = 15.4$ (degree)
Shaft immersion , $H = 1.26$ m
Axial advance speed , $V_a \cos \epsilon = 35 \cos (15.4) = 33.74$ knots
Cavitation number based on axial advance speed , $\sigma_V$
$\sigma_V = 0.75$ (otherwise we need to interpolate between two diagrams)

$B_p = 2.63$

Select 3 B.A.R’s and read-off P/D at optimum $\gamma_0$ and calculate the followings

\[
\eta_T = \frac{1}{2} \rho \frac{V_r^2}{N} = \left(11.66 \sqrt{V_a \cos \epsilon}\right)^2 + (0.828 N D)^2 \frac{N}{m^2} \left\{ \frac{\text{knots}}{\text{rpm}} \right. \}
\]

\[
A_E = \frac{A_p}{(1.067 - 0.229 \frac{P}{D})}
\]

B.A.R $= \frac{A_E}{A_0}$

\[
\bar{V}_R = \frac{P - e}{\frac{1}{2} \rho V_a^2}
\]

<table>
<thead>
<tr>
<th>B.A.R</th>
<th>0.8</th>
<th>0.95</th>
<th>1.10</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D$ (mm)</td>
<td>920</td>
<td>867</td>
<td>898</td>
</tr>
<tr>
<td>$P/D$</td>
<td>1.283</td>
<td>1.321</td>
<td>1.404</td>
</tr>
<tr>
<td>$V_0$</td>
<td>0.703</td>
<td>0.698</td>
<td>0.698</td>
</tr>
<tr>
<td>$C_R$</td>
<td>0.115</td>
<td>0.127</td>
<td>0.134</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>0.109</td>
<td>0.116</td>
<td>0.115</td>
</tr>
</tbody>
</table>
In general the highest efficiency will be found to correspond with the most favourable dimensions from the point of view of cavitation, but this may be checked by examining the amount of breakdown in relation to the openwater curves in atmospheris condition or by using the diagram, which indicates % blade area covered by cavitation as giren GAWN & BURRILL to assess the amount of blade area covered by cavitation.

When we plot our \((\gamma; \sigma)\) for B.A.R= 0.8, 0.95 & 1.10 on G&B Cavitation trend diagram, we note that 3 points lie in over 20 % back cavitation. As noticed increasing B.A.R makes fort he candidate propellers.

The cavitation trend diagram is based on horizontal shaft condition. Because of our inclined shaft we need to look at performance at inclined condition by using \(K_T\) vs \(J\) diagrams so.

<table>
<thead>
<tr>
<th>B.A.R</th>
<th>(\gamma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td>0.95</td>
</tr>
<tr>
<td>0.95</td>
<td>1.007</td>
</tr>
<tr>
<td>1.10</td>
<td>1.042</td>
</tr>
</tbody>
</table>
If we mark above operating points J’s on the appropriate $K_T$ vs J diagrams in the following pages, the operating point considered lies too close max $K_T$ for 3 propellers bearing in mind large shaft angle.

After some engineering considerations it was decided to use a diameter of 900 mm, P/D=1.24 and B.A.R=1.05 i.e slightly larger diameter. This has resulted in

$$\gamma=0.97$$

$$\gamma_0=0.684$$

i.e a slightly lower efficiency but reducing the effect of cavitation.

The above design approach is based traditional procedure. This can be further improved by using the local steps by using.

1-Standard series & cavitation diagram for initial sizing.

2-Lifting line for optimum Loading distribution

3-Lifting surface procedure for analysis of cavitation vibrations etc to improve blade section design.