上海交通大学

SHANGHAI JIAO TONG UNIVERSITY

# 螺旋桨设计

SHIP PRINCIPLE PROJECT–PROPELLER DESIGH


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# Contents

# 1 Introduction

The goal is to design a MAU right-handed propeller with five blades for a certain container ship.

# 2 Data

## 2.1 Main Parameters of the Container Ship

Table 1 gives the main parameters of the container ship.

| | | | |
|---|---|---|---|
| $L_{wl}$ | Design waterline | 215 | $m$ |
| $L_{pp}$ | Length between perpendiculars | 210 | $m$ |
| $B$ | Breadth | 32 | $m$ |
| $D$ | Depth | 12.7 | $m$ |
| $\Delta$ | Volume of displacement | 54000 | $m^3$ |
| $C_b$ | Block coefficient | 0.655 | - |

Table 1: Main Parameters

The datasheet of the ship's effective power in different speed has been given as Table 2.

| Ship Speed(kn) | Ballast(kW) | Full load(kW) | Super full load(kW) |
|---|---|---|---|
| 19 | 7542 | 9552 | 11323 |
| 19.5 | 8117 | 10275 | 12186 |
| 20 | 8861 | 11208 | 13303 |
| 20.5 | 9689 | 12247 | 14544 |
| 21 | 10562 | 13342 | 15855 |
| 21.5 | 11490 | 14506 | 17248 |
| 22 | 12532 | 15812 | 18811 |
| 22.5 | 13791 | 17389 | 20700 |
| 23 | 15420 | 19429 | 23143 |
| 23.5 | 17618 | 22181 | 26442 |
| 24 | 20634 | 25954 | 30966 |
| 24.5 | 24762 | 31118 | 37159 |
| 25 | 30345 | 38100 | 45533 |

Table 2: Effective Power

| | | | |
|---|---|---|---|
| $MCR$ | maximum continuous rating of main engine | 33000 | kW |
| N | rated speed | 102 | rpm |
| - | type of the propeller | MAU series | - |
| n | number of the blades | 5 | - |
| - | number of the propeller | 1 | - |
| - | direction of the propeller | right-handed | - |
| - | material of the propeller | Cu3 nickel aluminum bronze | - |
| $Z_p$ | distance between the boss and the base line | 4.7 | m |
| $d_h$ | diameter of the boss | 1.4 | m |

Table 3: Main Engine and Propeller

## 2.2 Parameters of Main Engine and Propeller

Parameters of main engine and propeller are shown in Tab. 3.

## 2.3 Design Conditions

| | |
|---|---|
| design condition | full load |
| design main engine power | $P_s = 0.85MCR = 28050kw$ |
| desing rotating speed | $N = 102rpm$ |

Table 4: Design Conditions

## 2.4 Propulsive Factors

| | | |
|---|---|---|
| $\omega$ | wake fraction | 0.25 |
| $t$ | thrust deduction fraction | 0.16 |
| $\eta_R$ | relative rotating efficiency | 1.0 |
| $\eta_s$ | shaft system efficiency | 0.98 |
| $\eta_H$ | ship hull efficiency | 1.12 |

Table 5: Propulsive Factors

# 3 Design for Maximum Ship Speed

In this part, we select a number of EARs(Extend Area Ratio), and determine a maximum ship speed for each of them.

## 3.1 Related Parameters

Firstly, the basic related parameters is shown in Tab 6.

| | |
|---|---|
| density of sea water($15°C$) | $\rho = 1025.91kg/m^3 = 104.63kgf \cdot s^2/m^4$ |
| main engine power | $P_s = 0.85MCR = 28050kw$ |
| receiveing power of propeller in open water | $P_D = \eta_s \eta_R P_s = 27209kW$ |
| rotating speed of propeller | N=102rpm=1.7rps |
| receiveing torque of propeller | $Q = \frac{P_D}{2\pi n} = 2.547^6 N \cdot m$ |

Table 6: Related Parameters in Speed Design

## 3.2 Assume Parameters

1. In the range of 0.5 to 0.8, we assume 7 EARs in equivilent distance.
2. For each EAR, assuming 21 diameters between 7.5m to 8.5m in the step of 0.05m.
3. For each diameter, assuming 21 crusing speed between 21kn to 25kn in the step of 0.2.
4. For each diameter, assuming 13 pitch ratios between 0.4 to 1.6 in the step of 0.1.
5. According to the torque equilibrium and using the regression formula, we can get different thrusts and torques in different pitch ratios for each diameter and cruising speed. Furthermore, we can get the right pitch ratio, the effective thrust and the open water efficiency using interpolation.
6. We can determine the cruising speed by interpolation when the effective thrust equals to the drag force for each diameter. Thus, the pitch ration can be set.
7. Choosing the maximum opening water efficiency，we can get the diameter accordingly.

We can do caculation in Matlab following the procedure above. The code is shown in Appendix. The result is in the Tab. 7.

# 4 Cavitation Check

Determine an EAR required for each propeller design to be cavitation-free, and subsequently determine the minimum EAR that ensures the propeller has the highest efficiency while being free of cavitation.

## 4.1 Related Parameters

Thus, we can caculate the differential pressure conditions:

$$p_0 - p_v = p_a + \gamma h_s - p_v = 10330 + 1025.91 \times 8 - 174 = 18363.28 kgf/m^2 \quad (1)$$

The principle equations are as follows:

$$\begin{cases} \sigma_{0.7R} = \frac{P_0 - P_v}{\frac{1}{2}\rho V_{0.7R}^2} \\ \tau = \frac{T/AP}{\frac{1}{2}\rho V_{0.7R}^2} \end{cases} \quad (2)$$

| EAR $\frac{A_E}{A_0}$ | Diameter D | Crusing Speed $V_s$ | Pitch Ratio $\frac{P}{D}$ |
|---|---|---|---|
| 0.50 | 7.7406 | 23.9632 | 0.9380 |
| 0.55 | 7.8925 | 23.9861 | 0.9087 |
| 0.60 | 7.6945 | 24.0030 | 0.9675 |
| 0.65 | 8.0147 | 24.0056 | 0.8948 |
| 0.70 | 7.8520 | 23.9855 | 0.9381 |
| 0.75 | 7.8476 | 23.9347 | 0.9392 |
| 0.80 | 8.1915 | 23.8449 | 0.8474 |
| **Advance Coefficient J** | **Thrust Coefficient $K_t$** | **Torque Coefficient $K_q$** | **Open Water Efficiency $\eta_0$** |
| 0.6457 | 0.1865 | 0.0309 | 0.7020 |
| 0.8643 | 0.1736 | 0.0280 | 0.6891 |
| 0.7365 | 0.1923 | 0.0316 | 0.7070 |
| 0.7062 | 0.1638 | 0.0259 | 0.6790 |
| 0.7166 | 0.1773 | 0.0288 | 0.6927 |
| 0.7167 | 0.1749 | 0.0288 | 0.6916 |
| 0.8297 | 0.1363 | 0.0214 | 0.6571 |

Table 7: Best Parameters for Design

| Depth of the boss | $h_s = D - Z_p = 8m$ |
|---|---|
| wake fraction | $\omega = 0.25$ |
| Sea water mass density($15°C$) | $\rho = 104.63kgf \cdot s^2/m^4$ |
| Sea water gravity density($15°C$) | $\gamma = 1025.91kg/m^3$ |
| Sea water vapor pressure($15°C$) | $p_v = 174kgf/m^2$ |
| Atmospheric pressure($15°C$) | $p_a = 10330kg/m^2$ |

Table 8: Basic Parameters

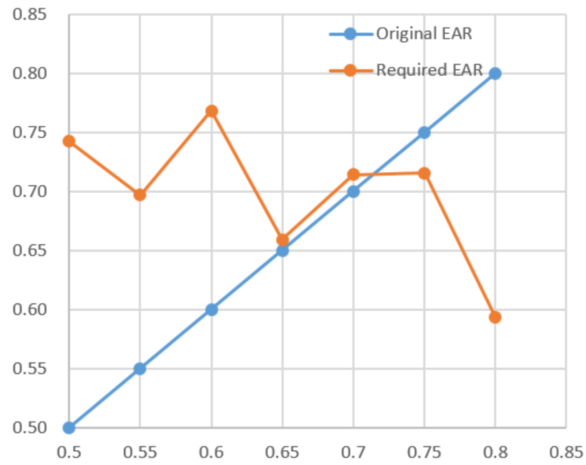


Figure 1: Cavitation Checking Result

In this part, it is convenient to use EXCEL and caculation sheet is shown in Appendix. The cavitation verification results are shown in Tab.9. According

| | | MAU5-50 | MAU5-55 | MAU5-60 | MAU5-65 | MAU5-70 | MAU5-75 | MAU5-80 |
|---|---|---|---|---|---|---|---|---|
| $V_max$ | kn | 23.9632 | 23.9861 | 24.0030 | 24.0056 | 23.9855 | 23.9347 | 23.8449 |
| D | m | 7.7406 | 7.8925 | 7.6945 | 8.0147 | 7.8520 | 7.8476 | 8.1915 |
| $\eta_0$ | - | 0.7020 | 0.6891 | 0.7070 | 0.6790 | 0.6927 | 0.6916 | 0.6571 |
| $V_{0.7R}^2$ | $m/s2$ | 922.8968 | 956.2511 | 913.2449 | 983.5733 | 947.3309 | 946.0171 | 1022.459 |
| $\sigma_{0.7R}$ | - | 0.3803 | 0.3671 | 0.3844 | 0.3569 | 0.3705 | 0.3710 | 0.3433 |
| $\tau_c$ | - | 0.1481 | 0.1425 | 0.1484 | 0.1393 | 0.1437 | 0.1439 | 0.1372 |
| $P/D$ | - | 0.9380 | 0.9087 | 0.9675 | 0.8948 | 0.9381 | 0.9392 | 0.8474 |
| $A_E/A_0$ | - | 0.7422 | 0.6968 | 0.7678 | 0.6592 | 0.7140 | 0.7153 | 0.5930 |

Table 9: Cavitation Check Results

to the result of EAR above, we can get the Fig.1. From the figure, the point of intersection of two curves is the EAR we want, which satisfies the conditions of maximum crusing speed, thrust equivalence. Meanwhile, we can get the minimum extend area ratio when there is no cavitation through interpolation. Furthermore, other best propeller factors can be achieved. The result is shown in Tab.10

| | | |
|---|---|---|
| Extend Area Ration(EAR) | $A_E/A_0$ | 0.7145 |
| Maximum Speed | $V_max$ | 23.9601kn |
| Diameter | D | 7.8498m |
| Pitch Ratio | $P/D$ | 0.9386 |
| Open Water Efficiency | $\eta_0$ | 0.6921 |

Table 10: Best Parameters of Propeller

# 5 Strength Check

Safty is one of the most important issues among the design.Aaccording to the principle of the "Rules and Regulations for the Construction and Classification of Sea Going Steel Ships" in 2001, we should check the $t_{0.25R}$ and $t_{0.6R}$ whether they are both bigger than the following value:

$$t = \sqrt{\frac{Y}{K - X}} \tag{3}$$

Specifically, X is called rotate speed coefficient and Y is called power coefficient, $K = 1.38$ is material factor of Cu3 nickel aluminum bronze.

## 5.1 Power Coefficient

$$Y = \frac{1.36 A_1 N_e}{Z b n_e} \tag{4}$$

$$A_1 = \frac{D}{P}(K_1 - K_2 \frac{D}{P_{0.7}}) + K_3 \frac{D}{P_{0.7}} - K_4 \tag{5}$$

The diameter of the propeller: $D = 7.8498m$
The pitch ratio in the section: $P = P_{0.7} = \frac{P}{D} D = 0.9386 \times 7.8498 = 7.3678$
$K_1 - K_4$ can be found in Tab.11
The main engine power: $N_e = 32010kw = 43551hp$
The number of blades: $Z = 5$
The rotating speed of propeller: $n_e = 102rpm$
According to the blades outline of the AU propeller, we can calculate the b:

$$b_{0.66R} = 0.266D \frac{EAR}{0.1Z} = 2.9838m \tag{6}$$

$b_{0.25R} = 0.7212 b_{0.66R} = 2.1519m$,$b_{0.6R} = 0.9911 b_{0.66R} = 2.9573m$.

| Radius | $K_1$ | $K_2$ | $K_3$ | $K_4$ | $K_5$ | $K_6$ | $K_7$ | $K_8$ |
|---|---|---|---|---|---|---|---|---|
| 0.25R | 634 | 250 | 1410 | 4 | 82 | 34 | 41 | 380 |
| 0.60R | 207 | 151 | 635 | 34 | 23 | 12 | 65 | 330 |

Table 11: K Factor Table of Different Radius of Propeller

## 5.2 Rotate Speed Coefficient

$$X = \frac{A_2 G A_d N^2 D^3}{10^{10} Z b} \tag{7}$$

$$A_2 = \frac{D}{P}(K_5 + K_6 \epsilon) + K_7 \epsilon + K_8 \tag{8}$$

$D, P, n_e, Z, b$ are the same with Y.
The back-inclined angle: $\epsilon = 10°$
The density of blades: $G = 7.6g \cdot cm^{-3}$
The extend area ratio: $A_d = 0.7145$

| | | 0.25R | 0.6R |
|---|---|---|---|
| b | m | 2.1519 | 2.9573 |
| A1 | | 1925.033 | 703.7262 |
| Y | | 76360.82 | 20312.47 |
| A2 | | 1249.445 | 1135.689 |
| X | | 0.317334 | 0.209887 |
| t | mm | 268.063 | 131.7551 |
| Standard | mm | 300.2549 | 171.1256 |
| Checking Results | | Satisfied | Satisfied |

Table 12: Strength checking

$K_5 - K_8$ can be found in Tab.11
Results of caculation of cavitation varification are shown in Tab.12.

As a result, we can determine the propeller's thickness in different radiuses as Tab.13 shows.

| $r/R$ | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 |
|---|---|---|---|---|---|---|---|---|---|
| $t/mm$ | 324.6 | 287.4 | 250.3 | 213.2 | 176.0 | 138.9 | 101.7 | 64.6 | 27.5 |

Table 13: The Propeller's Thickness in Different Radiuses

# 6 Pitch Ratio Modification

## 6.1 Different Hub to Diameter Ratios

MAU series five blades propeller's standard pitch ratio is 0.18. However, according to design, the ratio is $(\frac{d_h}{D})' = \frac{1.4}{7.8498} = 0.1783$. Thus, modification is needed.

$$\Delta\left(\frac{d_h}{D}\right)_b = \frac{1}{10}[(\frac{d_h}{D})' - (\frac{d_h}{D})] = -0.000165 \tag{9}$$

## 6.2 Different Blade Thickness Ratios

Because MAU series propeller's thickness fail to pass the strength varification, another modification is needed. Setting MAU5-80 as standard propeller to modifiy.
Standard Propeller $(\frac{t}{b})_{0.7R} = 0.04715$
$a_E = 0.8$
Real Propeller $(\frac{t}{b})'_{0.7R} = 0.05498$
$a'_E = (1 + 1.1[(\frac{d_h}{D})' - (\frac{d_h}{D})])\frac{A_E}{A_0} = 0.7132$

$$\Delta(\frac{t}{b})_{0.7R} = [(\frac{t}{b})'_{0.7R} - (\frac{t}{b})_{0.7R} \times \frac{a_E}{a'_E}] \times 0.75 = 0.001569 \tag{10}$$

$$1 - s = \frac{V_A}{NP} = \frac{30.866(1-w)V}{NP} = 0.6927 \tag{11}$$

$$\Delta(\frac{P}{D})_t = -2\frac{P}{D}(1-s)\Delta(\frac{t}{b})_{0.7R} = -0.00204 \tag{12}$$

### 6.3 Final Pitch Ratio

$$(\frac{P}{D})_m = \frac{P}{D} + \Delta(\frac{P}{D})_B + \Delta(\frac{P}{D})_t = 0.9364 \tag{13}$$

# 7 Calculation of Weight and Inertia Moment

## 7.1 The Weight and Length

The weight of the blades:

$$G_{b1} = 0.169\gamma Z b_{max}\left(0.5t_{0.2R} + t_{0.6R}\right)\left(1 - \frac{d}{D}\right)D = 41810.7788kgf \tag{14}$$

The length of the hub: $L_K = 0.2D = 1.5699m$
The weight of the hub:

$$G_n = \left(0.88 - 0.6\frac{d_0}{d}\right) l_K \gamma d^2 = 12743.1kgf \tag{15}$$

$$d_0 = 0.045 + 0.108\left(\frac{P_D}{N}\right)^{1/3} - \frac{KL_K}{2} = 0.78535 \tag{16}$$

Thus, the overall weight of the propeller $G = G_{b1} + G_n = 54553.9kgf$ The value of related parameters are given in Tab.14.

| | | | |
|---|---|---|---|
| $\gamma$ | $7600kgf/m^3$ | Z | 5 |
| $b_max = b_{0.66R}$ | 2.9838m | d | 1.4m |
| $t_{0.2R}$ | 324.6mm | $t_{0.6R}$ | 176mm |
| D | 7.8498m | $P_D$ | 43970.1hp |
| N | 102rpm | K | $\frac{1}{10}$ |

Table 14: Related Parameters of Weight and Length

## 7.2 Inertia

First, we caculate:

$$\frac{d}{D} = \frac{d_h}{D} = \frac{1.4}{7.8498} = 0.1783 \leq 0.18 \tag{17}$$

Thus, we can get:

$$I_{mp} = 0.0948\gamma Z b_{max}\left(0.5t_{0.2} + t_{0.6}\right)D^3 = 1758892.985kgf \cdot cm \cdot s^2 \tag{18}$$

# 8 Open Water Graph of Propeller

Considering propeller open water characteristics regression curve formula:

$$\begin{cases} K_T = \sum_{k=1}^{16} a_k \left(\frac{A_E}{A_0}\right)^{r_k} \left(\frac{P}{D}\right)^{s_k} J^{t_k} \\ 10K_Q = \sum_{k=1}^{23} b_k \left(\frac{A_E}{A_0}\right)^{u_k} \left(\frac{P}{D}\right)^{v_k} J^{w_k} \\ \eta_0 = \frac{K_T}{K_Q}\frac{J}{2\pi} \end{cases} \tag{19}$$

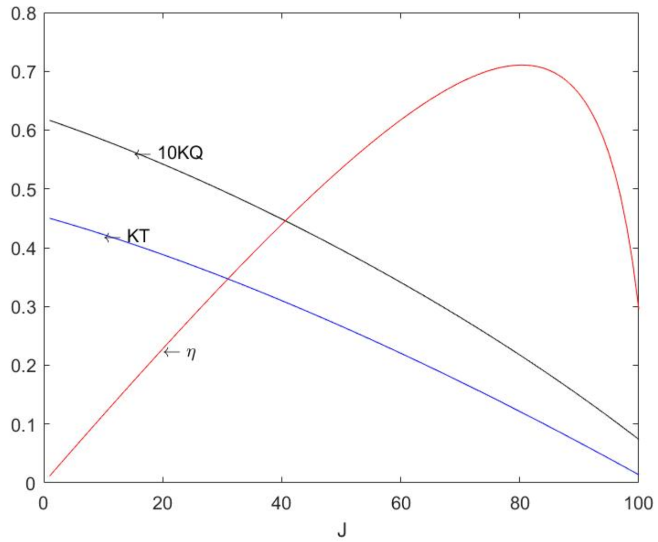


Figure 2: Open Water Graph

Related parameters are Extend Area Ratio $\frac{A_E}{A_0} = 0.7145$ and Pitch Ratio $\frac{P}{D} = 0.9364$. Now we can draw curves as Fig.2 shows.

# 9 Calculation of the Tied Column

From open water graph, we can get $K_T, K_Q$ when J=0 and do caculations. The result is shown in Tab.15.

| | | |
|---|---|---|
| J | | 0 |
| $K_T$ | | 0.4529 |
| $K_Q$ | | 0.62 |
| D | m | 7.8498 |
| power | KW | 32340 |
| tied column thrust deduction fraction | | 0.04 |
| main engine torque | N • m | 3027688.741 |
| tied column thrust | N | 281749.5722 |
| rotating speed of the propeller | r/s | 0.399807886 |

Table 15: Tied Column Characteristics

# 10 Calculation of the Cruising Characters

When the rotating speed equals to 102rpm, 97rpm, 92rpm, we can get the following results as Tab.16 shows and draw Fig.3.

| | Speed | 21 | 22 | 23 | 24 | 25 |
|---|---|---|---|---|---|---|
| | Advance Speed | 8.1025 | 8.4883 | 8.8741 | 9.2600 | 9.6458 |
| | Diameter | 7.8498 | 7.8498 | 7.8498 | 7.8498 | 7.8498 |
| | Pitch Ratio | 0.9364 | 0.9364 | 0.9364 | 0.9364 | 0.9364 |
| 102 | J | 0.6072 | 0.6361 | 0.6650 | 0.6939 | 0.7228 |
| | KT | 0.2170 | 0.2032 | 0.1892 | 0.1750 | 0.1607 |
| | KQ | 0.0337 | 0.0320 | 0.0303 | 0.0285 | 0.0267 |
| | Effective Power | 22151.6100 | 21730.3294 | 21153.3168 | 20418.1316 | 19522.3492 |
| | Main Engine Power | 32413.6127 | 30788.6961 | 29131.4690 | 27440.8480 | 25715.6250 |
| 95 | J | 0.6519 | 0.6830 | 0.7140 | 0.7450 | 0.7761 |
| | KT | 0.1956 | 0.1804 | 0.1651 | 0.1495 | 0.1337 |
| | KQ | 0.0311 | 0.0292 | 0.0273 | 0.0253 | 0.0233 |
| | Effective Power | 17316.9855 | 16736.5377 | 16007.3687 | 15127.0594 | 14093.1918 |
| | Main Engine Power | 24145.3232 | 22690.9451 | 21204.7782 | 19685.5318 | 18131.7809 |
| 85 | J | 0.7286 | 0.7633 | 0.7980 | 0.8327 | 0.8674 |
| | KT | 0.1578 | 0.1402 | 0.1224 | 0.1044 | 0.0861 |
| | KQ | 0.0264 | 0.0241 | 0.0219 | 0.0196 | 0.0172 |
| | Effective Power | 11182.7016 | 10413.1062 | 9504.8403 | 8455.4640 | 7262.5075 |
| | Main Engine Power | 14679.5793 | 13448.8532 | 12186.4460 | 10890.7113 | 9559.8528 |

Table 16: Cruising Results of the Ship

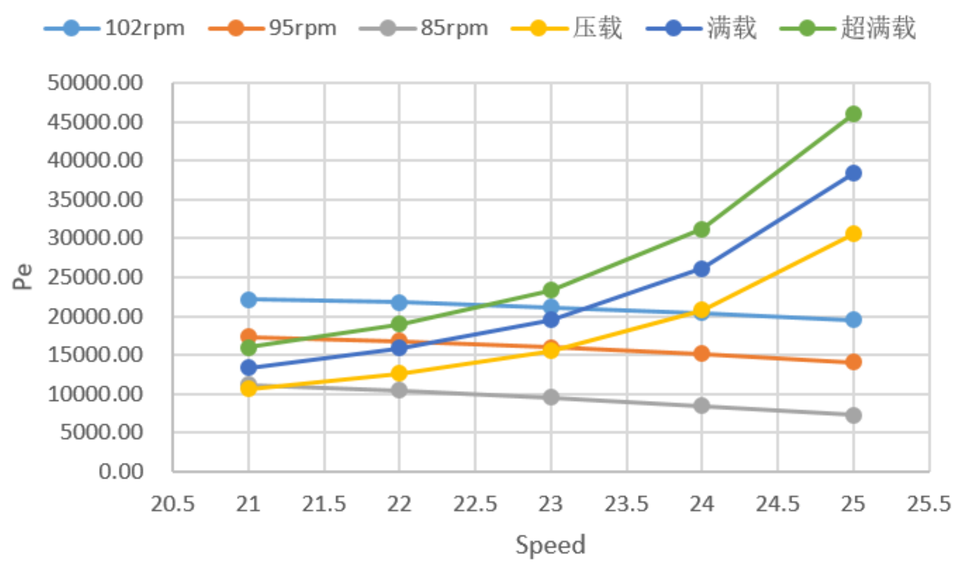


Figure 3: Cruising Characteristics Graph

According to the caculation results, we can get the maximum crusing speed and power of the main engine by interpolation as Tab.17 shows.

| Cruising Condition | Maximum Cruising Speed)(kn) | Power of Main Engine(w) |
|---|---|---|
| Ballast | 23.94 | 27546.97 |
| Fully Loaded | 23.22 | 28759.24 |
| Super Fully Loaded | 22.56 | 29868.74 |

Table 17: Final Results

## 11 Conclusion

Now, we have the ultimate design of the propeller. The data is shown in Tab.18.

| | | | |
|---|---|---|---|
| Diameter | $D$ | 7.8498 | $m$ |
| Pitch Ratio | $P/D$ | 0.9364 | - |
| Type | | MAU | |
| Number of Blades | $Z$ | 5 | - |
| EAR | $A_E/A_0$ | 0.7145 | - |
| Inclined Angle | $\epsilon$ | 10 | *degree* |
| Open Water Efficiency | $\eta_0$ | 0.6921 | - |
| Designed Cruising Speed | V | 23.9601 | *kn* |
| Ratio of boss to diameter | $d_h/D$ | 0.1783 | - |
| Rotating Direction | | Right | - |
| Material | | Cu3 nickle aluminum bronze | - |
| Weight | G | 54553.9 | *kgf* |
| Inertial Moment | I | 1758892.985 | $kgf \cdot cm \cdot s^2$ |

Table 18: Ultimate Design

## A Code

Listing 1: Caculate Max Speed

```
%初始化参数
n=1.7;  %螺旋桨转速rps
w=0.25; %伴流系数
t=0.16; %推力减额分数
% Pmax=33000000; %主机最大持续功率 W
% PS=0.85*Pmax;   %主机功率 W
% P_D=0.98*1*PS; %螺旋桨敞水收到功率 W
Q=2.547E6;          %螺旋桨收到转矩
den=1025.91;    %海水密度 kg/m^3
Result=zeros(40131,8); %
k=0;
%%-----------最大航速计算-----------%%
%计算出每种组合对应的kt, kq, eff
for EAR=0.5:0.05:0.8 %伸张面比 7个
```

```
for D=7.5:0.05:8.5 %直径 21个
for Vs=21:0.2:25 %航速 21个
for m=1:13
PD=0.1*m+0.3;%螺距比 pitch ratio 共13个
J=0.5144*(1-w)*Vs/(n*D); %计算进速系数J
[Kt, Kq]=calKtKq(J, EAR, PD);%计算推力系数Kt,转矩系数Kq
eta0 = (Kt./Kq)*(J/(2*pi));  %计算敞水效率eta0
Result(m+k,1)=EAR;       %计算结果矩阵第一列是伸张面比
Result(m+k,2)=D;         %第二列是直径
Result(m+k,3)=Vs;        %第三列是航速
Result(m+k,4)=J;         %第四列是进速系数
Result(m+k,5)=PD;        %第五列是螺距比
Result(m+k,6)=Kt;        %第六列是推力系数
Result(m+k,7)=Kq;        %第七列是转矩系数
Result(m+k,8)=eta0;      %第八列是敞水效率
end
k=k+13;
end
end
end

%%-------通过插值确定满足设计功率要求（即：螺旋桨要求的扭矩与设计功率
%%与转速下的收到转矩平衡）的螺距及相应的有效推力与敞水效率)--------%%
PD_req = findPD(Result, Q, den, n);

%%--------对每个直径，根据阻力曲线及不同航速下的有效推力值，通过插值
%%确定有效推力与阻力平衡的航速，以及对应的螺距和敞水效率----------%%
Vs_req = findVs(PD_req,den,n,w,t);
output = findD(Vs_req);


function [Kt,Kq]= calKtKq(J, EAR, PD)
%计算推力系数(Thrust Coefficient)Kt,转矩系数(Torque Coe.)Kq
%输入:进速系数(Advance Coe.)J, 伸张面比(Extend Area ...
    Ratio)EAR, 螺距比(Pitch Ratio)PD
%输出:推力系数(Thrust Coefficient)Kt,转矩系数(Torque Coe.)Kq
a=[0.05367018,-0.3023566,0.4333625,-0.1065471,-0.6582904,0.1189101, ...
    ...
-0.0004408557,-0.03317857,1.151124,0.1960773,-0.09747062,0.2036384, ...
    ...
-0.2566153,-0.1370242,-0.2874294,-0.2851609];
r=[0,0,0,1,3,1,0,1,2,3,1,0,1,0,2,1];
s=[0,0,1,0,2,1,6,1,2,0,3,1,1,0,0,2];
t=[0,1,0,2,0,3,0,4,0,0,0,1,1,2,0,0];
b=[-0.0925139,-0.1229,0.3050697,-0.2935303,-0.3991474,-1.02205,...
0.01022833,0.0035211,0.002552059,0.2143532,0.000713111,0.2078488,...
0.6397058,0.0009404846,-0.02930044,-0.07807623,-0.3025523,0.1855105,...
-0.672421,-0.2087142,0.9400654,0.9316346,-0.04348397];
u=[0,0,0,0,1,1,0,3,0,3,0,1,0,0,1,0,3,1,2,3,1,3,0];
v=[0,2,1,0,2,1,7,1,5,0,4,1,1,7,0,0,2,1,2,4,3,2,6];
w=[0,0,1,2,0,1,0,0,2,1,4,2,0,1,1,4,2,3,1,0,0,1,0];
Kt=0;
Kq=0;
for i=1:16
Kt=Kt+a(i)*(EAR)^(r(i))*(PD)^(s(i))*(J)^(t(i));
end
for i=1:23
Kq=Kq+(b(i)*(EAR)^(u(i))*(PD)^(v(i))*(J)^(w(i)))/10;
end

function PD_req = findPD(Result, Q, den, n)
%在某个螺旋桨直径下，通过插值确定满足设计功率要求（即：螺旋桨
```

```
%要求的扭矩与设计功率与转速下的收到转矩平衡）的螺距及相应的有效推力
%与敞水效率)
%输入:Result
%      螺旋桨收到转矩D, 海水密度den, 螺旋桨转速n
%输出:每个螺旋桨直径下合适的螺距比PD
k=1;
PD_req=zeros(length(Result)/13,8);
for i=1:1:length(Result)/13
Kq_req=Q/(den*n^2*Result(k,2)^5);%螺旋桨要求的扭矩
PD_req(i,1)=Result(k,1);%固定盘面比
PD_req(i,2)=Result(k,2);%固定直径
PD_req(i,3)=Result(k,3);%固定航速
%由扭矩系数插值得到螺距比
PD_req(i,4)=interp1(Result(k:k+12,7),Result(k:k+12,5),Kq_req,'spline');
%由扭矩系数插值得到敞水效率
PD_req(i,5)=interp1(Result(k:k+12,7),Result(k:k+12,8),Kq_req,'spline');
%由扭矩系数插值得到推力系数
PD_req(i,6)=interp1(Result(k:k+12,7),Result(k:k+12,6),Kq_req,'spline');
%由推力系数计算出的有效推力
PD_req(i,7)=PD_req(i,6)*den*n^2*Result(k,2)^4;
PD_req(i,8)=Kq_req;%对应扭矩系数
k=k+13;
end

function Vs_req = findVs(PD_req,den,n,w,t)
%到某一螺旋桨直径下设计所需的航速
%输入:海水密度den,螺旋桨转速n,伴流系数w,推力减额分数t
%输出:最优航速

Vs = PD_req(:,3);%从矩阵中提取航速
[ PE1, PE2, PE3 ] = calPE(Vs);%PE1压载功率, PE2满载功率, ...
    PE3超满载功率
R = (PE1.*1000)./(Vs.*0.514);%计算阻力
Kt2 = (R./PD_req(:,2).^4)./((1-t)*den*n^2);%计算需要的推力系数
Δ_Kt=Kt2-PD_req(:,6);

k=1;
PD_len=length(Kt2)/21;
Vs_req=zeros(PD_len,8);
for i=1:1:PD_len
Vs_req(i,1) = PD_req(k,1);%第一列盘面比
Vs_req(i,2) = PD_req(k,2);%第二列直径
%第三列插值确定需要的航速
Vs_req(i,3) = ...
    interp1(Δ_Kt(k:k+20,1),PD_req(k:k+20,3),0,'spline');
%第四列插值确定需要的螺距
Vs_req(i,4) = ...
    interp1(Δ_Kt(k:k+20,1),PD_req(k:k+20,4),0,'spline');
%第五列插值确定需要的效率
Vs_req(i,5) = ...
    interp1(Δ_Kt(k:k+20,1),PD_req(k:k+20,5),0,'spline');
%第六列插值确定需要的推力系数
Vs_req(i,6) = ...
    interp1(Δ_Kt(k:k+20,1),PD_req(k:k+20,6),0,'spline');
Vs_req(i,7) = PD_req(k,8);%第七列计算扭矩系数
Vs_req(i,8) = ...
    0.514*Vs_req(i,3)*(1-w)/n/Vs_req(i,2);%第八列计算进速系数
k=k+21;
end

function output = findD(Vs_req)
%插值求最大速度对应的直径%
```

```
k=1;
output=zeros(length(Vs_req)/21,8);
for i=1:length(Vs_req)/21
for j=1:10001
d=0.0001*j+7.4999;
v(i,j)=interp1(Vs_req(k:k+20,2),Vs_req(k:k+20,3),d,'spline');
end
vmax1=max(v');
vmax=vmax1(1,i);
d_max=interp1(Vs_req(k:k+20,3),Vs_req(k:k+20,2),vmax,'spline');
output(i,1)=Vs_req(k,1);            %v_d第一列为盘面比
output(i,2)=d_max;                %第二列是直径最优值
output(i,3)=vmax;                 %第三列是速度最大值
%第四列为螺距
output(i,4)=interp1(Vs_req(k:k+20,3),Vs_req(k:k+20,4),vmax,'spline');
%第五列为效率
output(i,5)=interp1(Vs_req(k:k+20,3),Vs_req(k:k+20,5),vmax,'spline');
%第六列为推力系数
output(i,6)=interp1(Vs_req(k:k+20,3),Vs_req(k:k+20,6),vmax,'spline');
%第七列为扭矩系数
output(i,7)=interp1(Vs_req(k:k+20,3),Vs_req(k:k+20,7),vmax,'spline');
%第八列为进速系数
output(i,8)=interp1(Vs_req(k:k+20,3),Vs_req(k:k+20,8),vmax,'spline');
k=k+21;
end

end
```

Listing 2: Open Water Caculate and Draw Graph

```
EAR=0.7145;PD=0.9364;
a=[0.05367018,-0.3023566,0.4333625,-0.1065471,-0.6582904,0.1189101, ...
    ...
-0.0004408557,-0.03317857,1.151124,0.1960773,-0.09747062,0.2036384, ...
    ...
-0.2566153,-0.1370242,-0.2874294,-0.2851609];
r=[0,0,0,1,3,1,0,1,2,3,1,0,1,0,2,1];
s=[0,0,1,0,2,1,6,1,2,0,3,1,1,0,0,2];
t=[0,1,0,2,0,3,0,4,0,0,0,1,1,2,0,0];
b=[-0.0925139,-0.1229,0.3050697,-0.2935303,-0.3991474,-1.02205, ...
0.01022833,0.0035211,0.002552059,0.2143532,0.000713111,0.2078488, ...
0.6397058,0.0009404846,-0.02930044,-0.07807623,-0.3025523,0.1855105, ...
-0.672421,-0.2087142,0.9400654,0.9316346,-0.04348397];
u=[0,0,0,0,1,1,0,3,0,3,0,1,0,0,1,0,3,1,2,3,1,3,0];
v=[0,2,1,0,2,1,7,1,5,0,4,1,1,7,0,0,2,1,2,4,3,2,6];
w=[0,0,1,2,0,1,0,0,2,1,4,2,0,1,1,4,2,3,1,0,0,1,0];
result=zeros(3,3);
for j=1:110
J=j/100;
KT=0;
for g=1:16
KT=KT+a(g)*(EAR)^(r(g))*(PD)^(s(g))*(J)^(t(g));
end
KQ=0;
for e=1:23
KQ=KQ+b(e)*(EAR)^(u(e))*(PD)^(v(e))*(J)^(w(e));
end
eta=KT/(KQ/10)*J/(2*pi);
result(j,1)=KT;
result(j,2)=KQ;
result(j,3)=eta;
```

```
end
J=1:1:100;
plot(J,result(1:100,1),'b');
text(10,result(10,1),'\leftarrow KT');
hold on
plot(J,result(1:100,2),'k');
text(15,result(15,2),'\leftarrow 10KQ');
hold on
plot(J,result(1:100,3),'r');
text(20,result(20,3),'\leftarrow \eta');
xlabel('J')
kt=0;
kq=0;
for g=1:16
kt=kt+a(g)*(EAR)^(r(g))*(PD)^(s(g))*(0)^(t(g));
end
for e=1:23
kq=kq+b(e)*(EAR)^(u(e))*(PD)^(v(e))*(0)^(w(e));
end
```

Listing 3: Caculate Cruising Characteristics

```
    J102=[0.607170003, 0.63608286, 0.664995717, 0.693908575, ...
        0.722821432];
    J95=[0.651908845, 0.682952123, 0.713995402, ...
        0.74503868, 0.776081959];
    J85=[0.728604003, 0.763299432, 0.797994861, ...
        0.83269029, 0.867385718];

    KT102=zeros(1,5);
    KQ102=zeros(1,5);
    KT95=zeros(1,5);
    KQ95=zeros(1,5);
    KT85=zeros(1,5);
    KQ85=zeros(1,5);
    for i=1:5
    [kt102, kq102]=calKtKq(J102(i),0.7145,0.9364);
    KT102(i)=kt102;
    KQ102(i)=kq102;
    [kt95, kq95]=calKtKq(J95(i),0.7145,0.9364);
    KT95(i)=kt95;
    KQ95(i)=kq95;
    [kt85, kq85]=calKtKq(J85(i),0.7145,0.9364);
    KT85(i)=kt85;
    KQ85(i)=kq85;
    end

    Vs=[21,22,23,24,25];
    [PE1, PE2, PE3] = calPE(Vs);

    function [ PE1, PE2, PE3 ] = calPE(Vs)
    %计算有效功率曲线
    %输入：航速
    %输出：PE1压载功率，PE2满载功率，PE3超满载功率
    c=[5.82329E6, -1.12816E6, 81927.6702, -2642.77266, 31.99959;
    7.28287E6, -1.41085E6, 102451.99935, -3304.68079, 40.01248;
    8.7346E6, -1.69215E6, 122883.80611, -3963.87495, 47.99561];
    PE1=0;
    PE2=0;
    PE3=0;
    for i=1:5
```

```
            PE1 = PE1 + c(1,i)*Vs.^(i-1);
            PE2 = PE2 + c(2,i)*Vs.^(i-1);
            PE3 = PE3 + c(3,i)*Vs.^(i-1);
        end
```

# B Cavitation Check Caculation Sheet

| 项目 | 单位 | MAU5-50 | MAU5-55 | MAU5-60 | MAU5-65 | MAU5-70 | MAU5-75 | MAU5-80 |
|---|---|---|---|---|---|---|---|---|
| 最大船速 | kn | 23.9632 | 23.9861 | 24.0030 | 24.0056 | 23.9855 | 23.9347 | 23.8449 |
| 螺旋桨直径 | m | 7.7406 | 7.8925 | 7.6945 | 8.0147 | 7.8520 | 7.8476 | 8.1915 |
| 敞水效率 $\eta_0$ | - | 0.7020 | 0.6891 | 0.7070 | 0.6790 | 0.6927 | 0.6916 | 0.6571 |
| 转速 | r/s | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 |
| 伴流分数 | - | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 |
| 螺旋桨收到功率 | kw | 27489 | 27489 | 27489 | 27489 | 27489 | 27489 | 27489 |
| 螺旋桨进速 | m/s | 9.245786 | 9.254595 | 9.261143 | 9.262119 | 9.254369 | 9.234787 | 9.20014 |
| $V^2_{0.7R}$ | m/s^2 | 922.8968 | 956.2511 | 913.2449 | 983.5733 | 947.3309 | 946.0171 | 1022.459 |
| 桨轴深沉 | m | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| 压力差$p_0$-$p_v$ | kgf/m^2 | 18363.28 | 18363.28 | 18363.28 | 18363.28 | 18363.28 | 18363.28 | 18363.28 |
| 空泡数 $\sigma$ | - | 0.380339 | 0.367073 | 0.384359 | 0.356876 | 0.370529 | 0.371044 | 0.343303 |
| 单位面积平均推力系数 $\tau_c$ | - | 0.1481 | 0.1425 | 0.1484 | 0.1393 | 0.1437 | 0.1439 | 0.1372 |
| 推力T | kgf | 212833.7 | 208725.8 | 213999.3 | 205492.1 | 209815.2 | 209916.1 | 200211.2 |
| 投射面积$A_P$ | m^2 | 29.765 | 29.27946 | 30.18318 | 28.6689 | 29.46133 | 29.47541 | 27.28112 |
| 螺距比P/D | - | 0.9380 | 0.9087 | 0.9675 | 0.8948 | 0.9381 | 0.9392 | 0.8474 |
| 展开面积$A_E$ | m^2 | 34.92703 | 34.08909 | 35.70147 | 33.2551 | 34.57178 | 34.59878 | 31.25173 |
| 盘面比$A_E/A_0$ | - | 0.742209 | 0.696785 | 0.767776 | 0.659157 | 0.713963 | 0.715311 | 0.593007 |

Figure 4: Cavitation Check Caculation Sheet