Semester Project : Hydrocontest Propeller Design

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1 Introduction

The Hydrocontest is a student competition which challenge is to build the fastest boat which consumes the least energy. The amount and source of energy is given in the form of an electrical motor with its battery. The students will be provided a starter kit which includes the motor, the boat an the hydrofoils. The ranking will be made according to the race time. The competition will be held in two categories :

- small displacement boats (such as personal watercraft)
- vessels for the transport of mass (container ships, oil...)

From the definition of the competition it clearly appears that the propulsion of the boat is a crucial issue. Therefore the choice of the propeller has to be made accurately to satisfy both categories of the competition.

This study's objective is to determine the main characteristics of an optimal propeller and to check if the propeller given with the starter kit is a valid starting point for the competitors. In other words : if needed or wanted, can the students participate to both categories with the given propeller?

2 Goals of the project

The hull of the boat is an optimist, it has a hole in the middle for the motor to be placed in. The whole structure is highly modular, allowing the positioning of the elements such as the foils. An overview of the boat is shown on figure 1.

Figure 1: Overview of the boat

The problem to be solved in this study is to determine whether the propeller given with the starter kit is suitable and to determine the range of propeller that can be more adapted to this kit. There are only a few properties of the kit that are useful in order to determine the characteristics of the propeller (cf. section 4):

- the torque of the shaft of the motor
- the rotational speed of the motor
- the thrust of the propeller, equivalent to the drag of the boat at constant speed
- some geometrical properties of the propeller

The nominal torque and rotational speed of the motor are known from the manufacturer, but the actual values at the shaft are not. They have to be determined. The same problem occurs with the drag of the boat which is completely unknown. The first step of this then to measure those quantities.

Once it has been done the two following approaches will be used :

1. knowing the optimal operating point of the motor, the size of the optimal propeller corresponding to this torque will be determined

2. knowing the drag, hence the thrust of the boat at constant speed, the size of the optimal propeller corresponding to this thrust will be determined

The next step will be to compare the analytical results with the real propeller and perhaps propose a good compromise solution.

3 Tests and measurements

3.1 Electrical measurements

The characterization of the motor have been done by the Laboratoire des Machines Electriques at the EPFL. The modus operandi of the tests is not known and is not the objective of the present study. Nevertheless the two most important characteristics of the motor have been obtained, the torque at the shaft for a specific rotational speed and the efficiency of this operating point. The results are presented at figure 10 and 11 respectively. The most efficient operating points, $e > 75\%$ can be found in table 1 where ϵ is the efficiency of the motor (conversion of electrical into mechanical power), n is the rotational speed in [rpm] and C is the torque in [Nm].

ϵ	75	78	78	78	79	79
n	1200	630	1140	1175	1046	1100
C	3.43	0.45	4.73	4.30	7.25	5.99

Table 1: Most effients operating points of the motor

The first impression given by the measurements of the motor is that the best operating point is $n = 1046$ (the green column in table 1) since it has the highest efficiency and also the highest torque at the shaft. However it does not mean that it will correspond to the most efficient propeller. The operating points that will be used to determine the optimal propeller are n =1046, 1100, 1140, 1175 and 1200.

3.2 Drag measurement

The drag of the boat cannot be measured directly. An indirect measure has to be taken. In this case the boat will be towed by another boat. The rope connecting the two boats will be connected to a strain sensor (in reality four strain sensors). Four strain sensors are used because each sensor are designed to work within a 25 kg (250 N) range of load. Since the expected drag will be superior to that value four sensors have been assembled in parallel in order to split the total drag. The disposition of the sensors is shown in figure 2. The strain measured by the sensors when the boat navigates at constant speed corresponds to the drag of the boat. The acquisition is made via Matlab by a script that continually reads the values of the sensor (every second). The speed of the boat is measured by a GPS tracker.

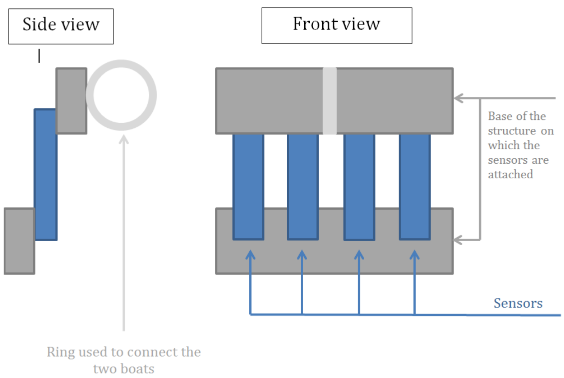

Figure 2: Schematic views of the strain sensors

The measurement of the drag has taken place on Lake Geneva near the port of Morges. The tests have been done on a low winded day. No actual measurements of the speed of the wind were maid but it felt like there was no wind. Once the two boats are tied up together and put into water, the trailer boat is kept at constant speed for a time interval of 30 seconds in order to allow the acquisition of enough data significant data. The data is then analyzed in Excel and Matlab. In order to calculate the drag of the boat, the data was segmented in intervals of constant speed. The mean value and the standard deviation of each interval were calculated. The evolution of the drag for the speeds 4.24 and 5.88 kts are shown on figure 3 and 4 respectively.

The speed are chosen for the following reasons :

- 4.24 kts corresponds the speed just before the boat arises on the water, it is assumed to be the speed that generates the maximum drag

- 5.88 kts corresponds the speed just after the boat arises on the water

The main assumption in the definition of these two speed is that the propeller has to work for the normal conditions of navigation during the race but also has to be able to lift the boat properly. It is then assumed that the worst case scenario is during the lifting of the boat, hence a proper range has to be define to calculate the size of the propeller. These two speeds give a good upper and lower limit to the range of the worst case scenario.

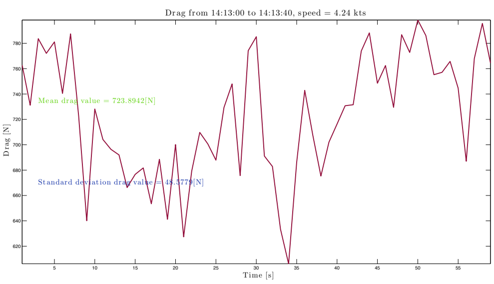

Figure 3: Evolution of the measured drag during 40 seconds at constant speed of 4.24 kts

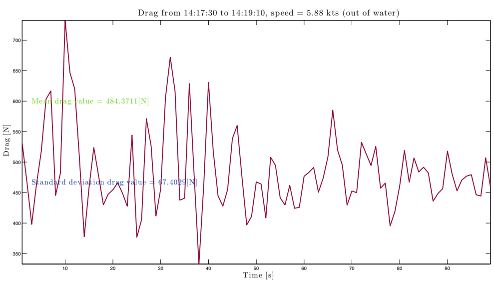

Figure 4: Evolution of the measured drag during 40 seconds at constant speed of 5.88 kts

4 Analytical analysis of the propeller

4.1 Geometrical properties of the propeller

The propeller is the dominant propulsion mechanism used in naval vehicles. Its main geometrical characteristics are presented in figure 5 and 6. From these two figures[1] it can be seen that the shape of a propeller is complex and generally not symmetric. For a more thorough insight, the lector can refer to [1].

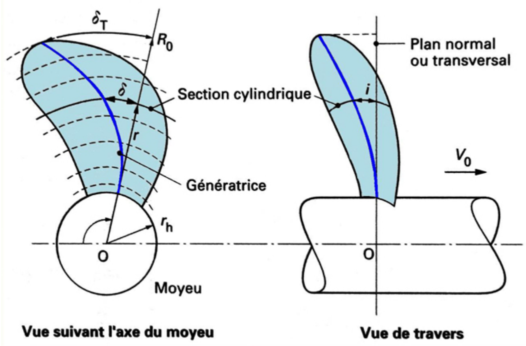

Figure 5: Generale shape of a propeller

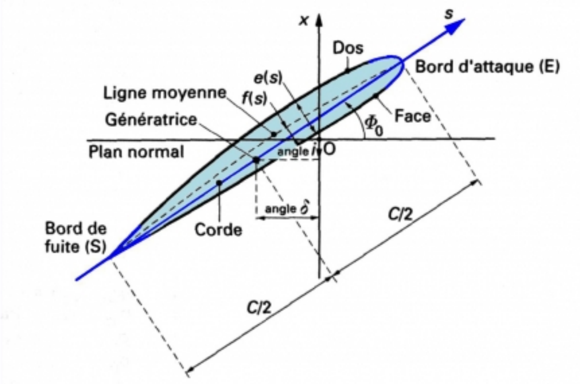

Figure 6: Geometry of the section of a blade at the radius r

The geometrical shape of the blade is entirely define at each position r along the blade, as can be seen in figure 6. The geometrical pitch is then defined for every r:

[1]Figures 5, 6,7,8 and 9 are taken from [1]

$$P(r) = 2\pi r \tan \phi_0(r)$$

Physically the pitch corresponds to the distance the propeller advances per revolution. The mean geometrical pitch corresponding to the whole propeller is then defined by:

$$\overline{P} = \int \frac{P(r)\mathrm{d}r}{R_0 - r_h}$$

The main geometrical properties are summarized in table 2.

Geometrical property	Definition and symbol
Diameter or radius of the propeller	D or R_0
Diameter or radius of the hub	d_{h} or r_{h}
Number of blades	Z
Mean pitch diameter ratio	$\overline{p}_0 = \overline{P}/D$
Chord lenght	$C(r)$
Disk area coefficient	A_{e}/A_0

Table 2: Geometrical properties of the propeller

4.2 Operating principle and characteristic coefficients

Consider a propeller moving through quiescent water at a constant speed V_0 in [m/s] with a rotational speed of $\omega = 2\pi n$ in [rad/s]. Its tangential speed is then $V_{\mathrm{t}} = \omega r$. These two speeds define the relative speed $V_{0\mathrm{R}}$ in an unperturbed flow (figure 7). The angle defined by the vector $\vec{V}_{0\mathrm{R}}$ and the axis Oz is called the angle of advance, it will be link further away with the advance number.

Physically it can be interpreted as the portion of rotating speed transformed by the propeller into advancing speed, or in other words the portion of ω transformed into V_0. Mathematically it can be written as :

$$\tan \beta(r) = \frac{V_0}{2\pi n r}$$

The propeller basically works like a wing with the addition of a rotational speed. In order to produced thrust, the propeller accelerates the water when passing through it and gives it an induced

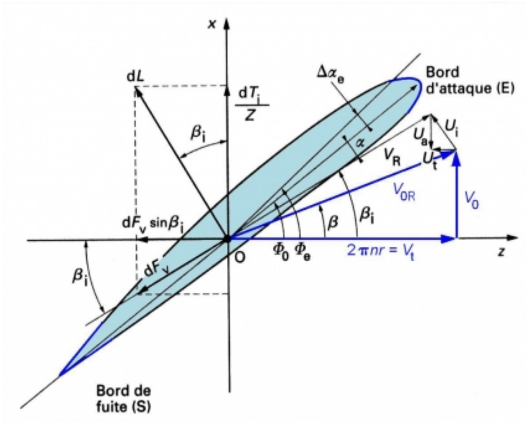

Figure 7: Balance of forces and velocities that apply to a section of the blade

velocity U_{i} (figure 7). This induced velocity is responsible of the relative speed V_{R} in disturbed water. Once the velocities are well defined, it is possible to calculate $\mathrm{d}L(r)$ (the lift) and $\mathrm{d}F_{\mathrm{v}}(r)$ (the drag) from the lifting line theory. It is then possible to express $\mathrm{d}T$ (the thurst) and $\mathrm{d}Q$ (the torque) as functions of $\mathrm{d}L$ and $\mathrm{d}F_{\mathrm{v}}$. For more detail the lector is referred to [1].

For practical applications it is interesting to define dimensionless coefficients. All these coefficients are introduced in relation to n, D and ρ, respectively the rotational speed, the diameter and the density of water[2]. The coefficients are:

$$J_0 = \frac{V_0}{nD} \tag{1}$$

The advance number which can be compared to the angle β presented in section 4.2.

$$K_{\mathrm{T}} = \frac{T}{\rho n^2 D^4} \tag{2}$$

The thrust coefficient.

$$K_{\mathrm{Q}} = \frac{Q}{\rho n^2 D^5} \tag{3}$$

The torque coefficient.

$$\eta_0 = \frac{K_{\mathrm{T}}}{K_{\mathrm{Q}}} \frac{J_0}{2\pi} \tag{4}$$

[2] The units used in this study for T, Q and n are N, N·m and tr/s but in the literature they can be found in t, t·m and rpm. In section 4.3 another units will be used specifically for some calculations

The propeller efficiency coefficient.

4.3 Optimum propeller

In order to calculate the optimum propeller, three different approaches will be used:

- in the first approach, the diameter of the propeller will be obtained by setting the torque Q for a given n and V_0.
- in the second approach, the diameter of the propeller will be obtained by setting the thrust T for a given n and V_0.
- in the third approach, the optimal K_T is known for different Z, and then using the definition of K_T and the value of T D_opt is calculated

Q based approach The objective of this approach is to determine a parameter B_p. This parameter is a function of the power $F = nQ$ expressed in cv, V_0 expressed in knots, n expressed in rpm and the mean wake $\overline{w}$ which is zero in this case (the propeller is underneath the boat as can be seen in figure 1 so it feels no wake).

$$B_\text{p} = \frac{n\sqrt{F}}{[V_0(1-\overline{w})]^{5/2}} \tag{5}$$

Once B_p is known the pitch diameter ratio P/D, the efficiency η_0 and the advance number J_0 can be read in the abacus shown on figure 8. Knowing J_0 the diameter D can be calculated.

T based approach This approach is the same as the Q based approach, with the difference that this time a parameter A_n is defined in function of T expressed in t, n expressed in tr/s, V_0 expressed in m/s and ρ expressed in t/m^3.

$$A_\text{n} = \frac{n^2 T}{\rho\,[V_0(1-\overline{w})]^4} \tag{6}$$

As before, the values of J_0 η_0 and P/D are read in the abacus shown on figure 9.

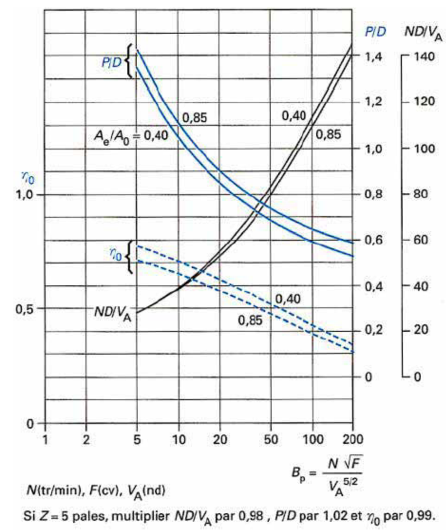

Figure 8: Abacus for the design of a 4 blade propeller in function of F, n and V_0

K_Topt based approach In this approach a completely different method is used. From [1] it is known that the optimal K_Topt depends mostly on the number of blades and very little on the pitch diameter ratio and the disk area coefficient. These values are shown on table 3

Z	3	4	5	6
K_Topt	0.14	0.17	0.19	0.20

Table 3: Optimal values of K_Topt in function of the number of blade Z

Having decided the number of blade, hence knowing K_Topt the diameter is determined using equation (2):

$$D_\text{opt} = \sqrt[4]{\frac{T}{\rho n^2 K_\text{Topt}}}$$

Once the diameter is known all the other coeffients can be calculated.

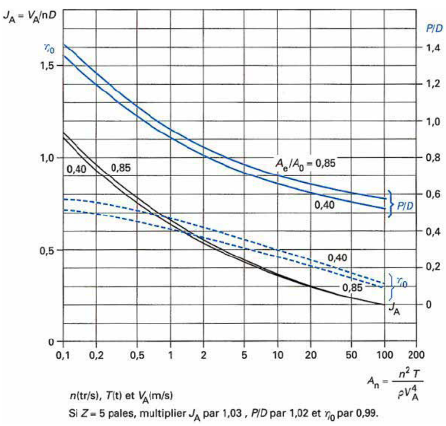

Figure 9: Abacus for the design of a 4 blade propeller in function of T, n and V_0

5 Results

5.1 Comparison of the results of the different methods

The results of the different approaches to determine the diameter are shown on figure 12. The first observation is that the difference in the results are in function of the velocity of the boat. For the Q based approach the diameter is bigger for 4.24 kts than for 5.88 kts (for n kept constant), whereas it is the contrary for the T and K_{Topt} approach. This can be explained by the definitions of the coefficient B_{p} and A_{n} (cf. equations (5) and (6)). As an illustrative example $B_{\mathrm{p}} = 12.96$ for $n = 1046$ at 5.88 kts whereas $A_{\mathrm{n}} = 0.1749$ for $n = 1046$ at 5.88 kts.

The second major observation is that the diameter of the propeller always decreases when n increases. This should not come as a surprise if one looks at the definition of K_{T} and K_{Q}. Reminding that $K_{\mathrm{T}} = T/(\rho n^2 D^4)$, if K_{T} ought to be kept constant with T kept constant and n increased, the diameter has then to deacrese. The same logic applies to K_{Q}. The tendency is valid for the three methods used.

The third major observation is that the diameter of the propeller depends on the number of blades used. As shown on figure 13, the more the blade the smaller the diameter. This is explained by the definition of the thrust and torque coefficient. As shown in table 3, as the number of blade increases K_{Topt} also increases. From the definition, $K_{\mathrm{T}} = T/(\rho n^2 D^4)$. This implies that for T and n kept constant, if K_{T} ought to be increased D has to decrease. Physically this affirmation makes sense since the thrust is produced by the lift generated around the blades, so more blades will produce more lift. In the same way bigger blades will produce more lift hence more thrust.

5.2 Sources of errors and differences

Two main sources of errors were identified to explain the differences in the results:

- imprecisions in the measurement of the drag of the boat
- imprecisions in the determination of B_{p} and A_{n} coefficients from the abacus 8 and 9

However it is important to note that the error may acount for some imprecisions in the exact size of the optimal diameter but globally not for the difference of range between the Q based approach and the ohter two approaches.

The difference in the results from the two approaches have one main reason. It is important to note that the calculation of B_{p} only takes into account the power of the motor at disposition and the speed wanted for this power. The actual conditions of sailing are unknown or not taken into account. On the other hand the calculation of A_{n} in made throught the thrust (hence the drag at constant speed) and the velocity wanted for this thrust. A_{n} is entirely dependent and aware of the conditions of sailing. In conclusion it can be said that is the Q based approach is more suited in determinig the optimal propeller diameter for a corresponding motor whereas the T based approaches are more suited in determining the optimal propeller diameter for a corresponding navigating condition.

5.3 Selection of the propeller and validation of the existing propeller

As seen in this section, there are many factors that influence the diameter of the propeller and many parameter to take into account. It is then important to remember the objectives of the present study; define an accurate range of diameter of propeller that work with the starter kit and check if the existing propeller given with the kit is valid. From the results shown in figure 12 it appears that the range varies from 11 cm to 27 cm. The actual propeller at disposition has a diameter of 9.25", which corresponds to approximately 23.5 cm. It also possesses 3 blades. The propeller is then within the range defined higher. Two other facts to take into account are [2] in the selection of the propeller are:

- the bigger the propeller the higher the efficiency
- the lower the number of blades the higher the efficiency

The optimal propeller for this boat should then have a diameter close to 27 cm and 2 or 3 blades.

6 Conclusion

In the present study the characteristics of an optimal propeller for the starter kit of the Hydrocontest competition have been studied. This optimal propeller should have the lowest possible number of blades and have a diameter in a range that goes from 11 cm to 27 cm. Ideally the diameter should be the biggest possible to maximize its efficiency. It has also be shown that the actual propeller which equips the starter kit is functional.

References

[1] M. Aucher, *Hélices Marines*, Techniques de l'ingénieur. Génie mécanique, 1996, vol. BL3, noB4360, pp. B4360.1-B4360.38, [Note(s): DocB4361.1]

[2] MAN Diesel & Turbo, *Basic Principles of Ship Propulsion*

[3] Sv. Aa. Harvald, *Resistance and Propulsion of Ships*, Volume 12 de Ocean engineering A Wiley-Interscience publication, 1983, Wiley

A Figures

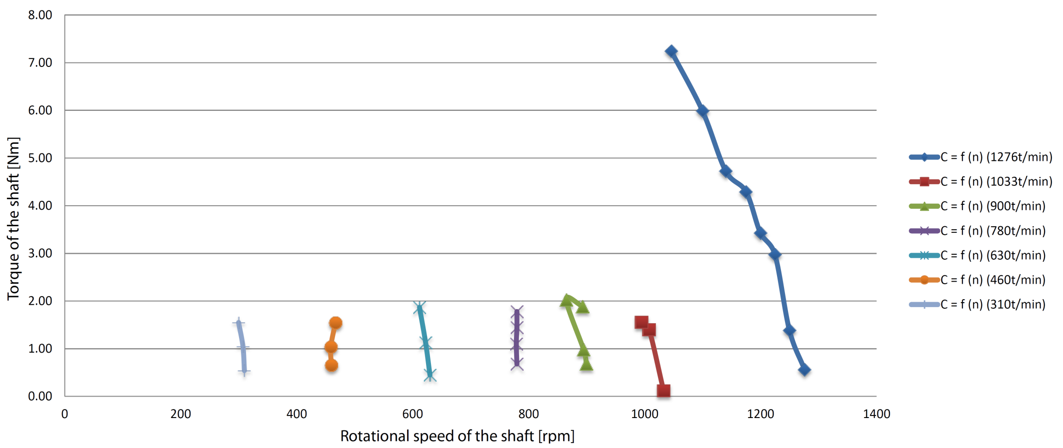

Figure 10: Torque on the shaft of the motor in function of the rotational speed

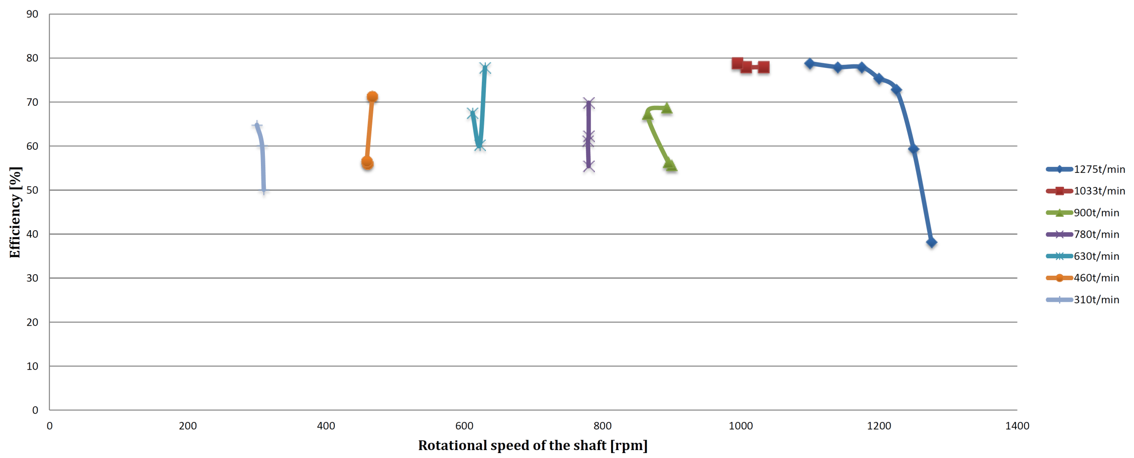

Figure 11: Efficiency of the motor in function of the rotational speed

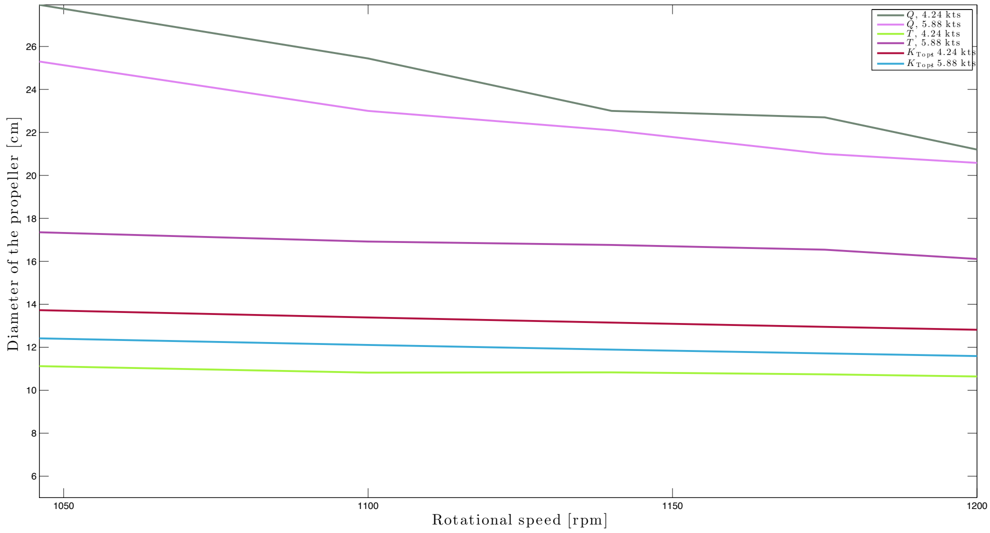

Figure 12: Diameter of a four blades propeller in function of the rotational speed and the advance speed calculated using the three differents approaches; Q based, T based and K_{Topt} based

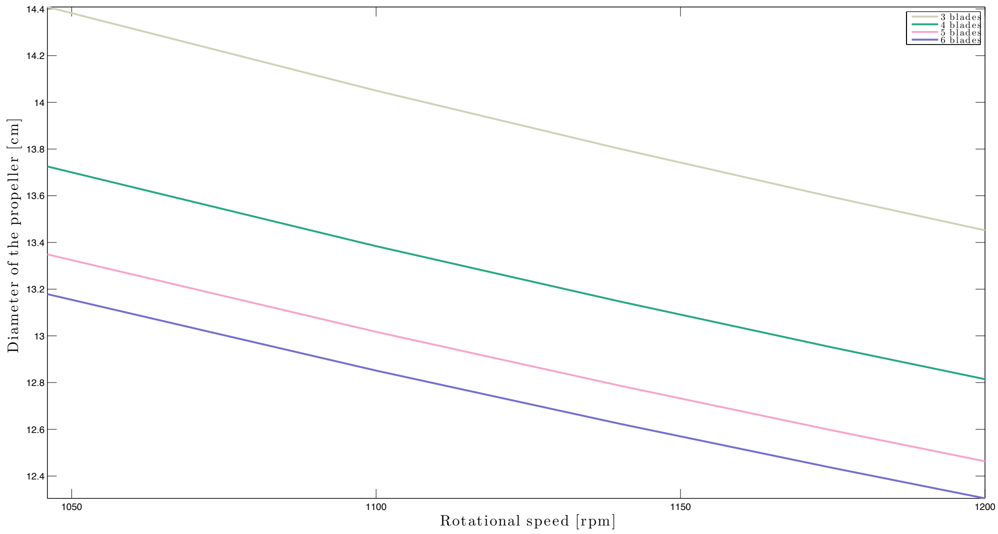

Figure 13: Diameter of the propeller in function of the rotational speed for an advance speed of 4.24 kts for different numbers of blades