Design of ducted propellers

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Introduction

The paternity of the marine propeller is highly disputed. The Austrian J. Russel in 1828, the Scot R. Wilson the same year, the French F. Sauvage in 1832, the English J. Ericsson in 1836 and several other inventors filed the patent. The legal battles that have accompanied these developments attest to the importance of the industrial challenge. Who is really the inventor? Everyone and no-one. The principle they applied was that of the worm screw illustrated by Leonardo da Vinci's famous engraving. This principle was already known to ancient Egyptians who used it to irrigate fields in the Nile Valley. But the operating principle of a propeller is not the same as a worm screw. The blades arranged around the hub act on the principle of the wing, the theory of which was not developed until the beginning of the 20th century by L. Prandtl. As for a wing, one of the two sides of the blade is in depression while the other is in overpressure and it is this pressure difference that is at the origin of the thrust force. To provide thrust, the propeller is rotated by an engine to which it is connected by the shaft line. Propulsive efficiency is the ratio between the propeller thrust power and the torque power provided by the engine.

The design of the propulsion system and therefore of the propeller consists in obtaining the best possible performance for the operating points corresponding to the vessel. For a ship that makes long crossings this operating point is unique since it almost always operates at the same speed. The propulsion efficiency for these vessels varies between 55 and 75% depending on the quality of the design. In the propulsion chain, the highest loss occurs at the propeller level. Under the best possible conditions, propeller efficiency can hardly exceed 80%.

Many ships do not have a single operating point. Military vessels, for example, because they have to cruise, patrol, monitor and sometimes quickly intervene. The worst off in this area are fishing vessels and especially trawlers. They must travel to and from fishing areas but also fish. The speed is then slow or very slow but the power required is very important because they have to pull the trawl behind them. For the propeller, this is the worst situation because it is extremely loaded; the pressure difference between the back and the belly of the blades is very large. The propeller efficiency can then be catastrophic, even less than 20%. The remaining 80% is wasted stirring water. The increase in the price of diesel fuel, the increasing scarcity of the resource and the environmental footprint no longer make it possible to accept such a waste. Although fuel economy was not the main focus, low performance was a problem. The theory shows that a loaded propeller wastes a lot of energy accelerating the fluid axially and the kinetic energy thus dissipated can easily be estimated; the rest of the loss is due to rotation and friction. An example of percentage of loss versus the thrust loading coefficient (C_{Th}) is shown in Figure 1. The same analysis has been performed changing the geometrical characteristics of the propeller blades, and it appeared that the most sensitive parameter is the maximum camber of the sections. The only way to partially counteract this effect and thus unload the propeller is to transfer part of the thrust to another appendix. This other appendix is the nozzle; a thick ring with a profiled section shape and inside which the propeller is placed. The first nozzle developed by Kort in 1934 was of this type. Since the highly charged propeller strongly accelerates the fluid axially, the pressure is reduced upstream of the propeller. By depressurizing the rounded wall inside the nozzle it is sucked forward creating a pushing force. Thus the nozzle participates in the thrust and reduces the propeller load. Under these conditions, the ducted propeller pushes more and has a better efficiency. The Dutch Maritime Research Institute has developed a series of results for open and ducted propellers using its test facilities and reported by Kuiper (1992). These results are commonly used to dimension the propellers. In the case of open water propellers, these results allow a first dimensioning before optimizing the geometry of the propeller. For ducted propellers, the tendency is to manufacture the ducted propeller directly based on the results without seeking to optimize it. This is an improvement compared to the propeller alone, but since we know that a trawler on average consumes one tonne of diesel fuel per tonne of fish caught, we should try to improve its performance.

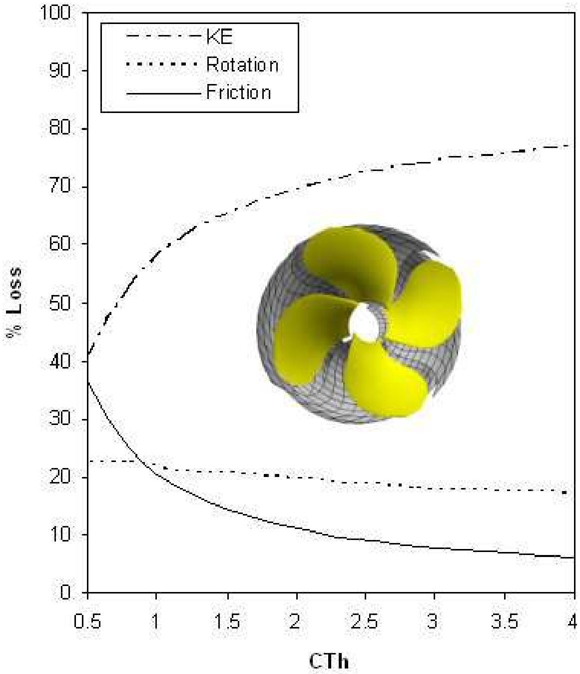
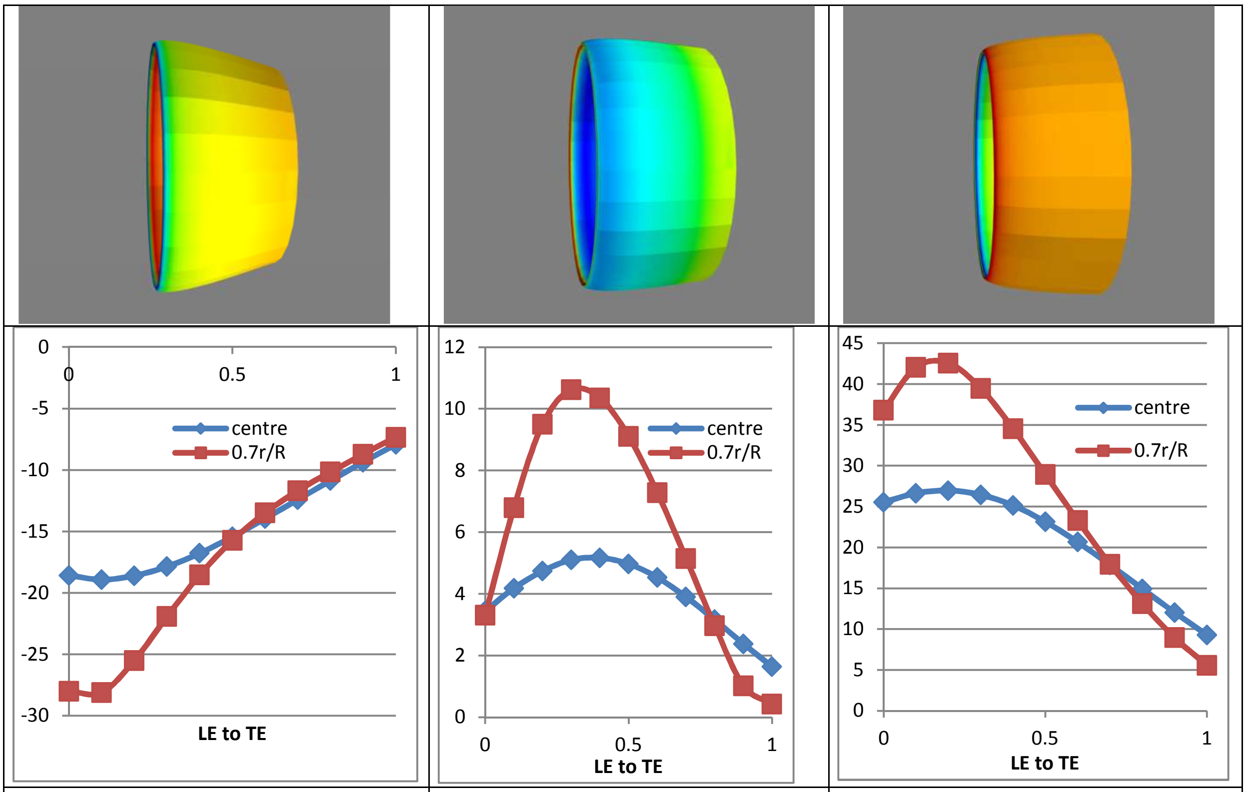


Figure 1 Percentage of loss of energy versus C_{Th} for a bare propeller. The kinetic energy loss (KE) becomes dominant when the thrust loading coefficient, C_{Th}, is important.

The first digital models to simulate ducted propellers date back to the 1960s, but finally there exist very few research projects in this field until recently with the very strong increase in crude oil from 2011 to 2014. The search for efficiency seems to follow the fluctuations of the oil market but research has a much greater inertia than stock markets and therefore solutions do not arrive fast enough and projects are abandoned until the next crisis. Environmental regulations provide a new element that will undoubtedly make it possible to continue research projects in the field of energy saving. Since 1960, the characterization and the design of ducted propellers have been the subjects of ongoing studies. One of the first fundamental papers, written by Morgan (1961), provided a ducted propeller analysis by modelling the duct according to the lifting line theory. In the late 1960s, Van Manen (1970) published an eminent paper on accelerating ducts and Kaplan propellers. Kerwin et al. (1987) published a fundamental analysis of the numerical modelling of ducted propellers . This study aimed to explain the use of potential flow theory in blade, hub, and duct numerical modelling. The panel code generated a complex mesh with helical panels named “extravaganza” by the authors. Subsequently, further research was carried out on this topic by Baltazar and Falcão de Campos (2009), Baltazar et al. (2012), and Laurens et al. (2012). Some research on the duct design demonstrated that ducted propellers are interesting in high loading blade conditions, such as fishing vessels Dasira and Laurens (2014). A recent paper by Gaggero et al. (2017) on the study of ducted propeller characteristics deserves to be cited. Their study aimed to characterize the flow swallowing in decelerating ducts, and how it influences propeller behaviour. Finally, few studies have been conducted on the characterization of parameters for ducted propeller design. This paper focuses on 3 ducted propellers, using only one rotor type: the Kaplan 4.55. We have very recently published a preliminary characterisation for numerical optimisation of ducted propellers, Remaud et al. (2019). Here we simply want to list the elements we must take into account to determine the optimisation strategy.

Duct section shape, circulation and trailing edge

We read in all handbooks that there are three types of duct: accelerating, decelerating and neutral. A lifting profile induces a circulation clockwise or anti-clockwise according to the direction of the lift. The flow through the duct is accelerated if the lift force is inward and decelerated if the lift force is outward. Although the phenomenon is easily understood, recent and less recent studies sometime ignore it and early numerical studies have to be retrieved like Van Manen and Oosterveld (1966). A ducted water turbine should therefore present a positive flare angle and/or a negative camber, Laurens et al. (2016). Heuristic reasoning provides a simple relationship between the section lift coefficient and the relative average acceleration, Remaud et al. (2019) but the detailed nominal flow is needed for an optimization procedure. Two computing procedures around the duct alone can be used: an axi-symmetric simulation of the real flow using a standard Navier-Stokes solver or a 3D potential flow. For this second procedure, the duct must be considered as a lifting body which imposes the use of the Kutta condition at the trailing edge of its profile and therefore a sharp trailing edge. Baltazar et al. (2009) showed that otherwise, the slightest variation for the position of the Kutta condition severely modifies the results. Both procedures are very fast and velocity profiles such as those presented in Figure 2 within the duct alone are easily obtained.



Negative flare: decelerating. | No flare: Neutral | Positive flare: accelerating

Figure 2: Percentage of axial velocity increase for decelerating, neutral and accelerating ducts. The circulation is induced by applying a flare angle to the symmetrical section.

The obtained velocities in the propeller disk are therefore equivalent to the nominal wake measured or computed behind the vessel. But before going any further the axial position of the propeller disk has to be decided.

Position of the rotor and preliminary parametric study

Like the propeller behind the ship, since the rotor accelerates the flow, it modifies the nominal wake. We can use the axi-symmetrical Navier-Stokes procedure combined with an actuator disk representation of the rotor and develop a procedure to obtain the effective wake, Hally and Laurens (1998). It must first be decided where the rotor will be placed axially. The answer may be obtained from the curves of Figure 2 but a preliminary parametric study reported in details in Remaud et al. (2019) showed that the answer is not so obvious. Three parameters of the duct geometry were considered in this study: the duct section thickness, the axial position of the rotor and the gap between the blade's tip and the inner duct. Like Saari (2014), we used the Kaplan 4.55 propeller with P/D=1 and the results are compared with the modified[i] 19A duct. The duct chord is half its diameter.

The configurations reported here are described in Table *1*.

Table 1 Configurations.

Configuration	**Profile**	**Gap/R**	**Rotor x-position**
Reference	19A-sharp	3.10 %	1/3
A	NACA0017	3.10 %	1/3
B	NACA0017	7.00 %	1/3
C	NACA0017	7.00 %	7/12
D	NACA0008	3.10%	1/3
E	NACA0008	7.00%	1/3
F	NACA0008	7.00%	7/12

At this stage, the propeller has not been modified but it should obviously have to be modified in a full design procedure. The complete results are shown in Table 2 and 3.

Table 2 Complete performance predictions for 3 configurations using the NACA0017.

	Reference			Configuration A			Configuration B			Configuration C		
J	KtD	Kt	Eta	KtD	Kt	Eta	KtD	Kt	Eta	KtD	Kt	Eta
0.45	0.035	0.209	0.540	0.035	0.238	0.537	0.037	0.245	0.543	*No results*		
0.5	0.027	0.193	0.576	0.028	0.215	0.575	0.031	0.222	0.583	0.047	0.288	0.624
0.55	0.020	0.177	0.606	0.023	0.191	0.609	0.025	0.198	0.617	0.039	0.259	0.662
0.6	0.014	0.161	0.630	0.018	0.168	0.637	0.019	0.174	0.645	0.031	0.230	0.695
0.65	0.008	0.144	0.647	0.013	0.144	0.656	0.014	0.150	0.666	0.024	0.200	0.721
0.7	0.003	0.126	0.652	0.009	0.120	0.665	0.010	0.126	0.677	0.018	0.171	0.739
0.75	-0.003	0.111	0.641	0.005	0.096	0.659	0.006	0.102	0.673	0.012	0.143	0.747
0.8	-0.006	0.089	0.621	0.002	0.073	0.632	0.003	0.078	0.650	0.007	0.114	0.742
0.85	-0.009	0.070	0.569	0.000	0.049	0.564	0.000	0.054	0.591	0.003	0.086	0.716
0.9	-0.011	0.050	0.470	-0.002	0.024	0.410	-0.002	0.029	0.459	0.000	0.059	0.651

Table 3 Performance predictions for the 3 configurations using NACA0008.

	Reference			Configuration D			Configuration E			Configuration F		
J	KtD	Kt	Eta	KtD	Kt	Eta	KtD	Kt	Eta	KtD	Kt	Eta
0.45	0.035	0.209	0.540	*No results*						0.057	0.273	0.587
0.50	0.027	0.193	0.576	0.025	0.180	0.565	0.036	0.207	0.599	0.056	0.256	0.644
0.55	0.020	0.177	0.606	0.020	0.162	0.598	0.030	0.190	0.636	0.045	0.235	0.681
0.60	0.014	0.161	0.630	0.015	0.144	0.624	0.024	0.172	0.669	0.036	0.213	0.714
0.65	0.008	0.144	0.647	0.011	0.125	0.641	0.019	0.154	0.696	0.029	0.192	0.743
0.70	0.003	0.126	0.652	0.007	0.105	0.648	0.014	0.136	0.715	0.022	0.169	0.766
0.75	-0.003	0.111	0.641	0.004	0.085	0.640	0.010	0.116	0.726	0.016	0.146	0.781
0.80	-0.006	0.089	0.621	0.001	0.065	0.605	0.007	0.097	0.724	0.011	0.123	0.786
0.85	-0.009	0.070	0.569	-0.001	0.043	0.525	0.004	0.076	0.704	0.007	0.100	0.778
0.90	-0.011	0.050	0.470	-0.003	0.020	0.333	0.002	0.055	0.651	0.004	0.077	0.746

The results show that neutral NACA profiles can provide higher performance predictions than the accelerating Kort nozzle 19A. A smaller gap slightly changes the maximum circulation along the propeller blade but does not prevent the tip vortex and the resultant 3D effect. This observation explains why configuration A is not more efficient than configuration B. As expected, the hierarchy of the results is the same as the maximum thickness is changed; however and more surprisingly, the values are slightly higher for the smaller maximum thickness. These results tend to show that not only does reducing the duct section thickness increase the propeller diameter, but it also ensures a better performance.

Conclusion

This preliminary analysis has provided interesting perspectives on improving ducted propeller efficiency and performance predictions. The results of this study showed that a ducted propeller can be made more efficient by changing the geometry of the duct and the position of the rotor and more surprisingly that the ducted propeller can present a higher overall efficiency coefficient than the bare propeller.

In order to develop a complete design procedure to optimize a ducted propeller according to its operational purpose, we must first have a deep understanding of the interaction. The different numerical procedures mentioned here have to be involved and ideally experimental results are needed.

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[i] Since the potential flow code is used we had to modify trailing edge of the 19a duct section shape as explained in the previous section. The modified section shows a sharp trailing edge but the results are almost identical.