Distributed propulsion for ships

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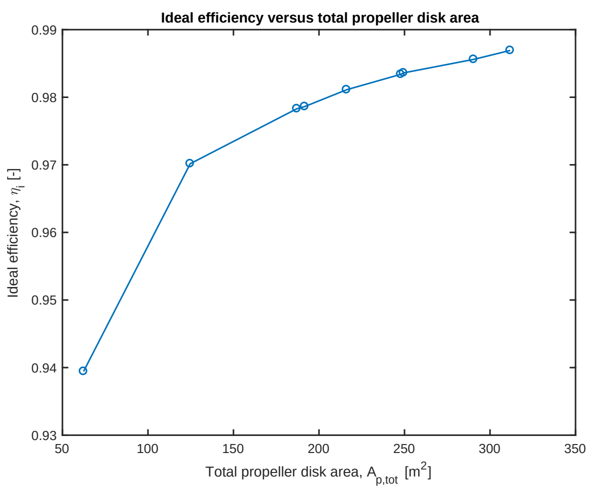
Introduction

When designing a modern cargo ship, a propulsion system with single or double screw propeller is usually preferred. This is mainly due to practical reasons as it is not efficient to use several small combustion engines. However, with electrical propulsion comes new possibilities of using configurations of small engines in strategical locations.
It is anticipated that applying distributed electrical propulsion (DEP) to conventional ships can increase the propulsive efficiency. This is mainly due to two reasons:

- The total propeller disk area can be increased
- Each propeller can be optimised for operation in a specific part of the wake

In the below figure is illustrated how the ideal efficiency of the DEP configurations in this work depends on the total propeller disk area.



Objective and scope

The main objective of this work was to investigate the use of DEP with sufficient accuracy to conclude if it can be beneficial for conventional cargo ships.
A 14000 TEU container ship with a single screw propeller was used as test vessel. Various configurations of DEP were analysed using lifting line theory to determine the thrust and torque of each propeller. Emphasis was placed on programming a lifting line code in MatLab that could estimate propeller performance with sufficient accuracy. In such a code, the propeller geometry is required as input. An optimisation algorithm was used to find the optimal geometry of each propeller in the configurations.
An open source program called Xfoil was used to calculate the lift coefficient due to camber and minimum pressure coefficient of each propeller blade section. These procedures were implemented into the code work in MatLab.
The limitations of the analysis are as follows

- The blade section geometry of the Wageningen B-screw series was used
- Interaction effects between the propellers were not accounted for
- Skew and rake were not included

Aknowledgements

The idea of using DEP on ships was suggested by my co-supervisor, Jarle A. Kramer. I would like to thank him and my supervisor, Sverre Steen, for all support and guidance.

Lifting line (LL) theory

The propeller blades were discretised into 30 foil sections and analysed for five angular positions using LL theory. This was determined based on a convergence test. The induced velocities were calculated for each blade section by solving the following equation numerically. The integration was conducted in the radial direction of the blades, from hub, r_h, to tip.

$$U_{A,T}(r_0) = \frac{1}{2\pi}\int_{r_h}^{R} I_{A,T}(\beta_i, Z, r_0)\frac{\partial\Gamma(r)/\partial r}{r_0 - r}dr$$

This led to an iterative procedure as the radial circulation distribution, $\Gamma(r)$, and induced hydrodynamic angle of attack, β_i, were unknown. The induction factors, I_A and I_T, were calculated according to [1].
When the circulation and induced velocities were determined, the thrust and torque from each blade section were calculated as follows

$$dT = \rho\Gamma(2\pi rn - U_T)dr - dDsin(\beta_i)$$
$$dQ = \rho\Gamma(V_A + U_A)dr \cdot r - dDcos(\beta_i)\cdot r$$

Where the advance velocity, V_A, was determined based on nominal wake fractions. dD represents the frictional drag force, while the induced drag is included in the above equations for dT and dQ.
Thrust and torque from each propeller were found as the sum over dT and dQ, respectively, and average of the angular positions. The propulsive efficiency was then calculated as

$$\eta_D = \frac{T\cdot V_S}{P}\cdot(1-t)$$

Where t is the thrust deduction fraction.

Optimisation

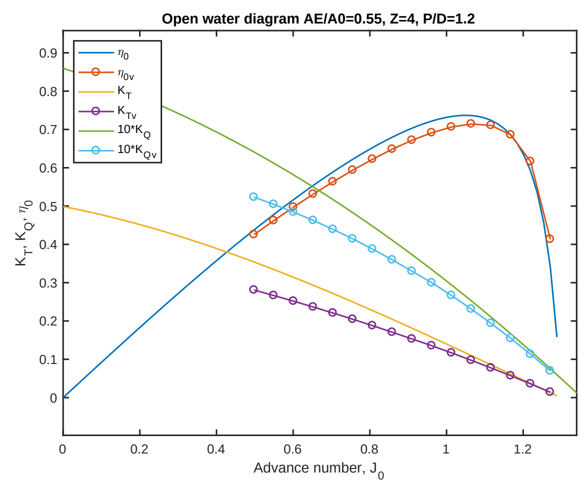
An interior-point algorithm, implemented in the function "fmincon" in MatLab, was used to find the optimal propeller geometry.
The objective was to minimise the effect delivered to the propellers, P, without cavitation and with the propellers providing the required thrust, T_{req}, to maintain operational speed.
The RPM was optimised for each propeller, while all propellers had the same blade area relationship in each configuration. The pitch was adjusted for each propeller by iteration such that the effective angle of attack was sufficiently small to prevent cavitation.

$$obj = min\left(\frac{P}{T_{req}\cdot V_S} + \mu_T(1 - \frac{T}{T_{req}})^2\right)$$

A quadratic penalty method was used to force the total thrust to be within 3% of T_{req}. This can be seen in the last term of the objective function.

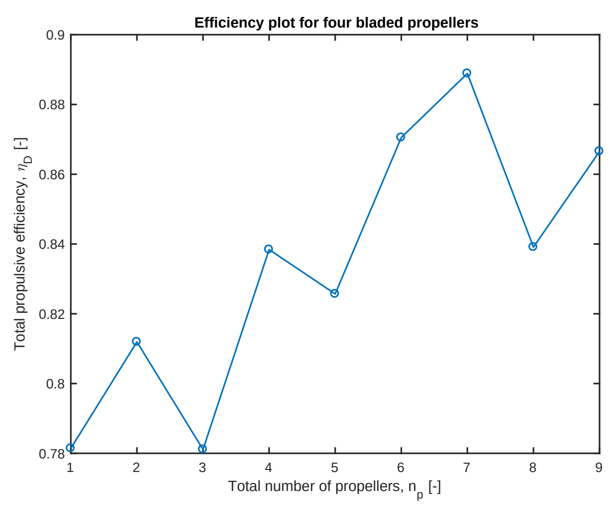
Validation

Prior to inclusion of wake, the LL code was validated against the open water diagrams given in [2]. One of the diagrams is shown below. LL results are subscripted v.

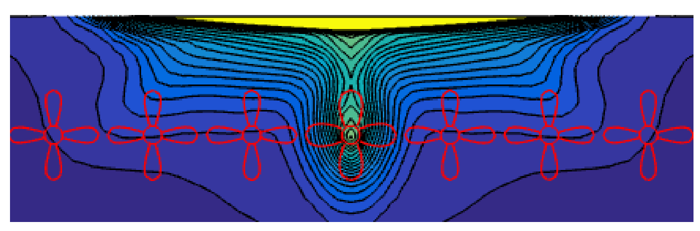


Results and conclusion

Below is plotted the propulsive efficiency of configurations with one to nine propellers in one row. Based on validation of the LL code, only four bladed propellers were analysed.



From potential theory it was expected that a configuration of five propellers would be most efficient. The influence of nominal wake are anticipated to be the reason why the seven propellers shown below are most efficient. Nevertheless, based on this work it is concluded that the propulsive efficiency can be significantly increased by the application of DEP. However, more extensive analysis are recommended and practical challenges remains to be investigated.



Resulting disk area and efficiencies for the configurations analyzed

row/col	1/1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9
$A_{p,tot}[m^2]$	62.4	124.7	187.1	249.4	311.8	290.4	247.8	216.2	191.7
$\eta_D[-]$	0.78	0.81	0.78	0.84	0.83	0.87	0.89	0.84	0.87

References

[1] van Oossanen, P. (197-?). Calculation of performance and cavitation characteristics of propellers including effects of non-uniform flow and viscosity.
[2] Oosterveld, M.W.C. and van Oossanen, P. (1975). Further computer-analyzed data of the Wageningen B-screw series, International Shipbuilding Progress, Vol 22, Number 251.