Mapping Noise and Efficiency for Marine Propeller Designs

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ABSTRACT

The primary aim of a marine propeller is to propel a ship to a given speed. Other desirable objectives might then be to do this as quietly, and as efficiently as possible. This paper presents a general framework for mapping out the noise and efficiency space as we vary gross propeller design parameters such as diameter, blade area or pitch-diameter ratios. For propellers, thrust and efficiency are usually presented as functions of advance ratio, and may be estimated using computational methods, theoretical expressions or curves derived from experiments such as those for the Wageningen B-Series. In the test framework, we maintain the desired ship speed and the corresponding thrust as a fixed overarching requirement. This essentially determines an advance ratio for each potential propeller in a large pool of randomly generated designs. Propellers which cannot deliver the required thrust are discarded. We may insert other criteria such as cavitation onset or material stress conditions to further refine the pool of potential designs before generating a noise estimate for each remaining propeller. In this work, an empirical radiated propeller flow noise estimate is used as the noise criteria. It is demonstrated that, even in this highly idealised setting, efficiency and noise have a complicated trade-off space.

1. INTRODUCTION

It can be said that marine propeller design involves part science and part art. Despite advances in modelling and analysis, choosing the appropriate propeller that delivers enough thrust to suit a ship’s operational profile still requires compromise between competing requirements. This paper investigates a methodology for exploring the trade-off space for two important propeller performance characteristics, viz., efficiency and noise. Improved propeller efficiency results in an extended range and lower running costs. A lower level of radiated noise improves acoustic survey capability and results in lower levels of on-board vibration levels, consequently improving crew habitability. Limiting waterborne noise from ships has received more attention in recent times. For example, the International Council for the Exploration of the Seas (ICES) has established guidance on the appropriate limits of waterborne underwater noise (Miston, 1995).

Propeller noise is a complex phenomenon, comprising both broadband and tonal components from diverse sources such as blade-blade interaction, blade-wake interaction, trailing edge scattering and vortex development in the turbulent wake, plus others (Blake, 1986). An example of an idealised noise spectrum, for a cavitating propeller, is shown in Figure 1. Although the makeup of propeller noise is multifaceted, general trends still exist. For example, it can be said that a large and fast speed propeller will generally produce more total acoustic energy than a smaller, lower speed propeller.

Efficiency for propellers is defined as the effective power produced in the water divided by the power delivered to the shaft. It is natural to regard maximal efficiency as the ultimate goal in propeller design, although this may be at odds with other goals. Traditionally, propeller performance is summarised by dimensionless coefficients for thrust K_T and torque K_Q as functions of advance ratio $J = U/nD$, where U is advance speed, n is shaft rate and D is diameter. Efficiency η is then given by $\eta = K_T J/2\pi K_Q$. The thrust, torque and efficiency characteristics of a propeller depend heavily on the geometry of the blades. In the general case, K_T, K_Q and η curves may be derived through progressively analysing blade sections from hub to tip as lifting surfaces, then summing the resultant forces (Gur and Rosen, 2008). Standardised propeller series, such as the Wageningen B-Series, were developed to help understand these performance characteristics in the case of highly proscribed blade geometry (Bernitsas et al., 1981). The performance curves for the Wageningen B-Series were determined through open-water experiments, with the thrust and torque coefficients cast as functions of advance ratio together with other fundamental gross design parameters: pitch-diameter ratio, blade-area ratio and number of blades. The thrust and efficiency curves for a class of 4-bladed Wageningen B-Series propellers have been reproduced in Figure 2.

We present a framework for evaluating propeller noise and efficiency in the early design phase. This can be used as a rapid assessment tool for "what if" analysis, rather than an optimisation method, although it does have similarities to design optimisation approaches such as those taken in Gaafary et al. (2011) and Benini (2003). The focus in Gaafary et al. (2011) is the optimisation of thrust coefficient and efficiency, with advance coefficient folded in to the optimisation step. In Benini (2003), a genetic algorithm is used to expose Pareto-optimal designs, again with maximum thrust coefficient and efficiency as objectives. In this work we treat radiated noise as a target for minimisation, and aim to illustrate the complex interdependency even very simple propeller noise models have with efficiency. Our approach also differs in that we treat the advance coefficient as being determined by the target operational speed, similar to Motley and Young (2011).

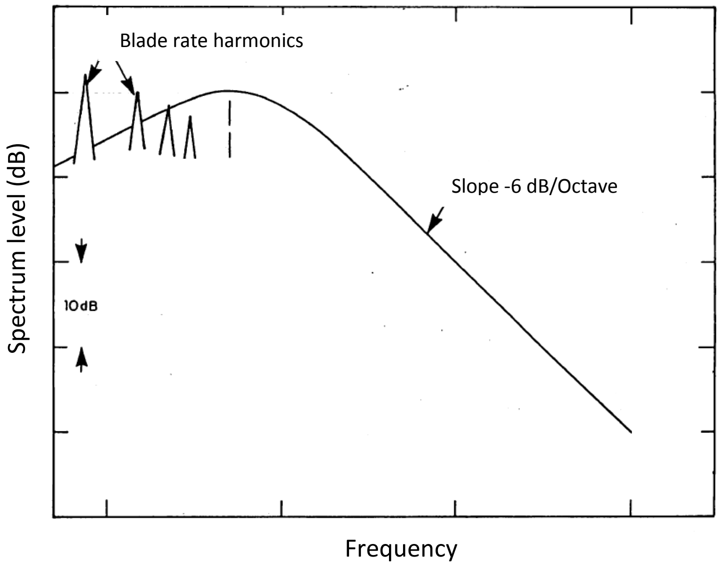

Figure 1: An example of an idealized propeller noise spectrum (Spence and Fischer, 2016)

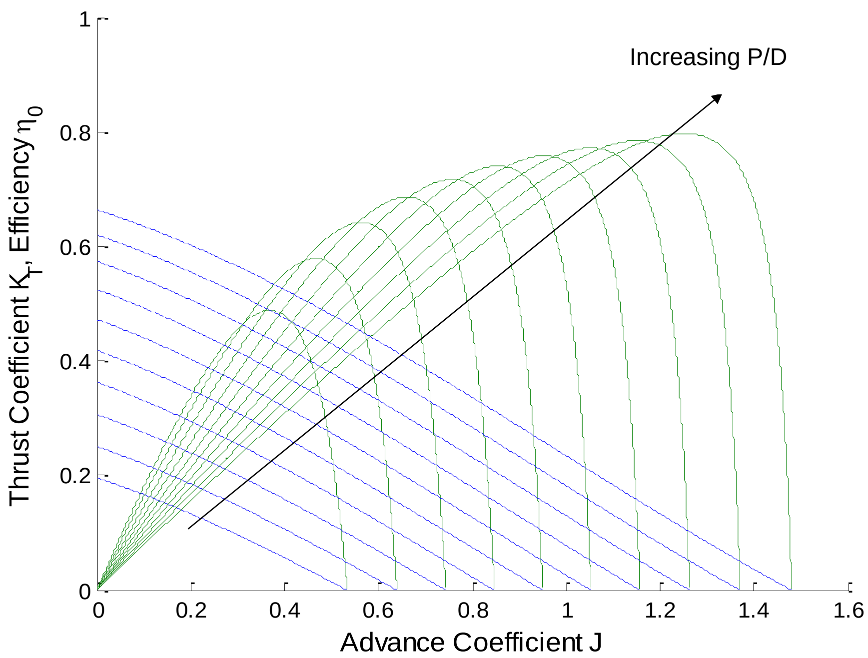

Figure 2: Thrust coefficient K_T and efficiency η curves for 4-bladed Wageningen B-Series propellers with blade-area ratio of 0.8 and pitch-diameter ratios ranging from 0.5 to 1.4 (Bernitsas et al. 1981).

2. ALGORITHM DESCRIPTION

Given a candidate ship and its operational speed, our aim is to map out a space of viable propeller designs that could drive the ship at the given speed, with efficiency and radiated noise being the main focii. By ``propeller'', we mean a collection of gross design parameters, which include: tip and hub radii, a representative chord length, pitch-diameter ratio, etc. The process can be extended to detailed geometry variation. Along with a noise estimate, other criteria may be inserted and tested at various stages, such as cavitation inception speed or material stress conditions. The process begins by generating a large pool of random propellers within chosen limits, then for each propeller, constraints are tested and a shaft speed is found that could potentially deliver the required thrust. The ones that fail conditions or cannot deliver the required thrust are dropped or labelled in some way, with those that remain tracing out a space of viable designs with their calculated noise and efficiency estimates.

The main over-arching constraint is the estimated thrust required to propel the ship at speed U. For this paper, this thrust T_{req} is given by the conventional expression

$$T_{req} = \frac{1}{2}\rho c_D L^2 U^2 \tag{1}$$

where ρ is the fluid density, c_D is a fixed representative drag coefficient for the candidate ship and L is the length scale (taken to be ship length). The aim is to match each propeller's resultant thrust with this required thrust, but at this stage, constraints that depend on thrust but not on propeller dynamics may be inserted. The Keller cavitation criterion for minimum blade area is an example of such a constraint.

For each propeller, thrust coefficient K_T and efficiency η curves are generated as functions of advance ratio J, making use of either general empirical approximations; known explicit formulae such as the open water polynomials for the Wageningen B-Series; or possibly a full inline blade-element analysis. More detailed models allow for greater degrees of variation in propeller geometry, along with greater computational costs.

The aim now is to match the propeller's calculated thrust with the required thrust T_{req} by finding a suitable advance ratio J'. With speed U and diameter D remaining fixed within this scope, determining this $J' = U/nD$ is essentially determining the required shaft speed n. Note that, for simplicity here, we are equating ship speed U with the propeller's advance speed V_a. This is open to refinement, as more precisely $V_a = U(1 - w)$ for some wake fraction w (Carlton, 2012). More precisely, by definition the thrust generated by each propeller, viewed as a function of J, is

$$T_{prop}(J) = \rho \left(\frac{UD}{J}\right)^2 \cdot K_T(J) \tag{2}$$

The next step is to numerically solve for J' so that $T_{prop}(J') = T_{req}$, within a given tolerance. Parallel criteria here are that the corresponding efficiency $\eta(J')$ must be greater than some realistic threshold, and that $J' \leq J_{max\eta}$, where $J_{max\eta}$ is the advance ratio associated with the point of maximum efficiency for the propeller. If no such J' can be found, the propeller is discarded.

For the remaining propellers, with their determined shaft speeds $n = U/J'D$, we may test other dynamic criteria such as material strength conditions.

Finally, noise estimates are produced for the surviving propellers. These may consist of empirical trailing edge noise models, turbulence ingestion or other calculations. We outline a simple tip vortex noise model in Section 2.2. As with the thrust and efficiency calculations, more complex models may be inserted at more computational cost.

The structure of the process may be summarised as follows:

- Calculate required thrust $T_{req} = \frac{1}{2}\rho c_D L^2 U^2$ and choose a minimum efficiency threshold η_{min}.
- Generate a large random set of propellers P.
- For each propeller $p \in P$:

1. Test constraints depending on thrust but not shaft speed (Keller cavitation criterion, blade stress etc)
2. Generate thrust coefficient K_T and efficiency η curves
3. Find the maximum efficiency η_{max} and corresponding $J_{max\eta}$
4. Determine J' so that $T_p(J') = \rho\left(\frac{UD}{J'}\right)^2 K_T(J') = T_{req}$ and $0 \leq J' \leq J_{max\eta}$ and $\eta(J') > \eta_{min}$
5. If such a J' can be found store the corresponding shaft speed $n_p = \frac{U}{J'D}$, otherwise drop p
6. Test constraints depending on shaft speed (material strength minimum thickness, etc)
7. If all passed produce a radiated noise estimate for p

2.1 Propeller Properties

Working through a large number of propellers, the framework relies on an efficient method for generating thrust coefficient and efficiency curves. The curves also need to be sufficiently resolved so that an advance ratio may be found such that T_{prop} is close to T_{req} within an acceptable tolerance. There are a number of options:

In the simplest case, we may restrict ourselves to the well-known and readily computable polynomials for the fixed design Wageningen B-Series (Bernitsas et al., 1981). This affords the most rapid computational performance, but allows for variation across only a few parameters: pitch-diameter ratio $0.5 \leq P/D \leq 1.4$, blade area ratio $0.3 \leq A_E/A_0 \leq 1.05$, and number of blades $2 \leq Z \leq 7$. Another drawback is that the polynomials are known to become more inaccurate towards the extremities of each parameter (Oosterveld and Van Oossanen, 1975).

At the other end of the spectrum, it may be possible to incorporate a blade element routine, allowing for a great deal of flexibility in geometric variation, at greater computational cost. Alternatively, closed empirical approximations such as those of Blake (1986) may be used as a compromise between speed and detail. These are commonly based on averaging the lifting surface calculations of a blade at a representative radius, the equations allow for a good deal of variation in overall blade design while remaining quickly computable.

2.2 Noise Model

For the purposes of this paper, we use a simple tip vortex noise approximation to demonstrate the methodology. Following Haddle and Skudrzyk (1969), the far field power spectral density for radiated flow noise for a body moving at velocity u through a fluid of density ρ and sound speed c, inducing a boundary layer thickness of δ, is roughly

$$W \approx 10^{-6}\frac{\rho^2 u^7}{c^4}\delta. \tag{3}$$

For a rotating propeller moving axially at velocity U, the speed of flow at the blade tips is $u = \sqrt{U^2 + (\pi n D)^2}$ where n is the shaft speed (in revolutions per second) and D is the diameter. In our scenario, the forward speed is typically much less than the tangential tip speed, that is $U \ll \pi n D$, and we may further simplify $u \approx \pi n D$. Following Oshima (1990), the boundary layer thickness δ may be approximated by $\bar{C}Re^{-k}$ where $\bar{C}$ is the average chord of a blade, Re is Reynolds number and k is a constant taken to be $1/5$. Making this substitution together with $Re = \frac{u\bar{C}}{\nu} \approx \frac{\pi n D\bar{C}}{\nu}$ where ν is the kinematic viscosity of seawater, we have

$$W \propto \frac{\rho^2 u^{7-k} \bar{C}^{1-k}}{c^4 \nu^{-k}} \approx \frac{\rho^2 n^{7-k} D^{7-k} \bar{C}^{1-k}}{c^4 \nu^{-k}} \quad (4)$$

This broad estimate for the tip vortex spectrum level obscures any directional or frequency dependent subtleties, but acts as a quickly computable upper bound for one component of the total acoustic energy as a function of shaft speed, diameter and average chord. In our context, shaft speed has a particularly non-linear relationship with propeller design and the required thrust. For a fixed ship speed, a larger diameter propeller will generally require less shaft speed than a smaller propeller, other design aspects being equal.

For Wageningen B-Series propellers, the average chord (taken at 0.7 tip radii) is related to blade-area ratio A_E/A_0, diameter D and number of blades Z by the formula

$$\bar{C} = \begin{cases} (2.168 \cdot D \cdot A_E/A_0)/Z \ for\ Z = 2{,}3 \\ (2.144 \cdot D \cdot A_E/A_0)/Z \ \ otherwise. \end{cases} \quad (5)$$

3. CASE STUDY

Consider a small survey vessel 40 m in length, 2.5 m draft with a single screw around 2m diameter and a target non-cavitating speed of 5 knots (2.57 ms^{-1}). A good first approximation for the drag coefficient of a ship hull, assuming the drag is friction dominated, is that of a flat plate in turbulent flow. For this work, a value of 0.003 has been chosen (Schlichting, 1968). The total thrust required in this scenario is subsequently found to be 16 kN. We use the Wageningen B-Series as a model for the propeller, and source thrust coefficient and efficiency polynomials from those given in Bernitsas et al. (1981) with the associated Reynolds corrections outlined in (Oosterveld and Van Oossanen (1975)). Note that these polynomials, fitted to open-water experiments, may not fully capture the thrust and efficiency characteristics of a real-world Wageningen B-Series in the turbulent wake behind the hull of the vessel.

To demonstrate the methodology, noise is modelled using the power-law tip vortex noise estimate given in Section 2.2. To avoid absolute estimates of noise here we will examine the difference between different propeller designs against a reference propeller, using the standard conversion to decibels $L_p(dB) = 10\log_{10}(W/W_0)$, where W_0 is the spectrum level for the reference propeller.

Under the assumption that for quiet operation a propeller should not cavitate, we include the Keller cavitation criterion for minimum blade area ratio. Introduced in Oosterveld and Van Oossanen (1975), the minimum for single screws is calculated to be

$$(A_E/A_0)_{min} \geq \frac{(1.3 + 0.3Z)T}{(p_0 - p_V)D^2} + 0.2 \quad (6)$$

where T is the propeller thrust (which we equate with T_{req}), Z is the number of blades, D is the diameter, p_0 is the static pressure at the centre line of the propeller and p_V is the vapour pressure. For blade area ratios less than $(A_E/A_0)_{min}$, the propeller is more likely to be cavitating. It should be noted that this does not include the effect of the hull on cavitation inception.

Note that seawater properties such as density and kinematic viscosity are used repeatedly throughout the code. Internally, we use the MIT Thermophysical Properties of Seawater library (Nayar et al., 2016, Sharqawy et al., 2010) as a consistent source for deriving these environmental properties. For this case study, the sea water temperature and salinity were chosen to be 10 degC and 34 ppt.

Figure 3 shows a baseline plot of efficiency versus relative radiated noise for 4-bladed, 2m diameter propellers, with the Keller cavitation criterion added as a static constraint (blade areas less than the Keller minimum in red; greater than in blue). Blade area ratio A_E/A_0 and pitch-diameter ratio P/D are varied between the limits $0.3 \leq A_E\ /\ A_0\ \leq 1.05$ and $0.5 \leq P\ /\ D \leq 1.4$. It can be seen that efficiency and noise are broadly correlated, with less efficient designs being generally noisier. Towards the more optimal area, the relationship becomes more complex. The green +-sign indicates an arbitrarily chosen reference propeller with $A_E\ /\ A_0\ = 0.7$ and $P\ /\ D = 1.0$.

In Figure 4, we show the effect of changing diameter slightly. In this plot we have discarded propellers with a blade area ratio less than the Keller minimum. For the diameters 1.8m (mustard), 2.0m (blue) and 2.2m (teal) we see there is a region of overlap, with differences in efficiency, noise and interaction with the Keller minimum becoming apparent towards the region of quieter designs. As expected, larger diameter propellers are generally more efficient in providing the same thrust, also requiring much less shaft speed, evidently leading to marginally better acoustic performance at the extremities. It should be kept in mind that this study does not include other limiting factors on diameter, such as the hull-wake interplay, blade stress or other related noise mechanisms.

In Figure 5 we have traced the Pareto-optimal front for 2m propellers, with efficiency and relative noise as objectives to maximise and minimise, respectively. When the Pareto front is convex, it can be exposed by using a simple parameterised weighted sum as the cost function in a multiobjective optimisation

$$P(s) = \min\left[sW + \frac{(1-s)}{\eta_0}\right] \tag{7}$$

with $0 \le s \le 1$.

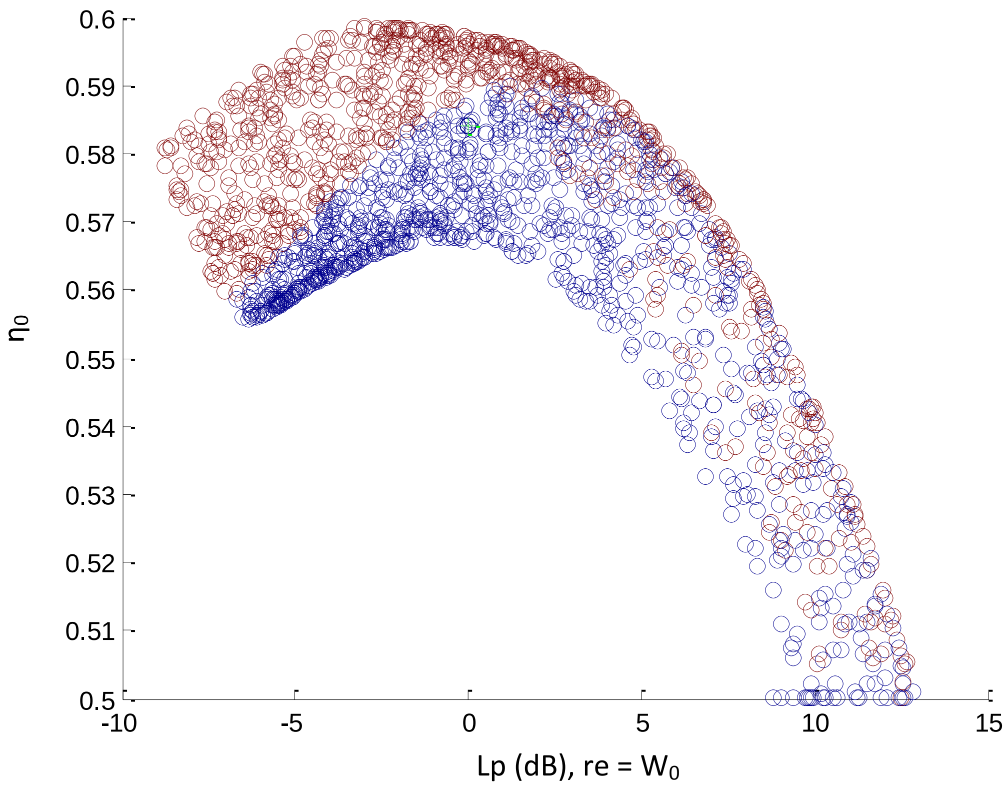

Figure 3: Efficiency against relative tip vortex noise for various 4 bladed, 2 m diameter Wageningen propellers. The red points violate the Keller cavitation criterion, the blue points do not.

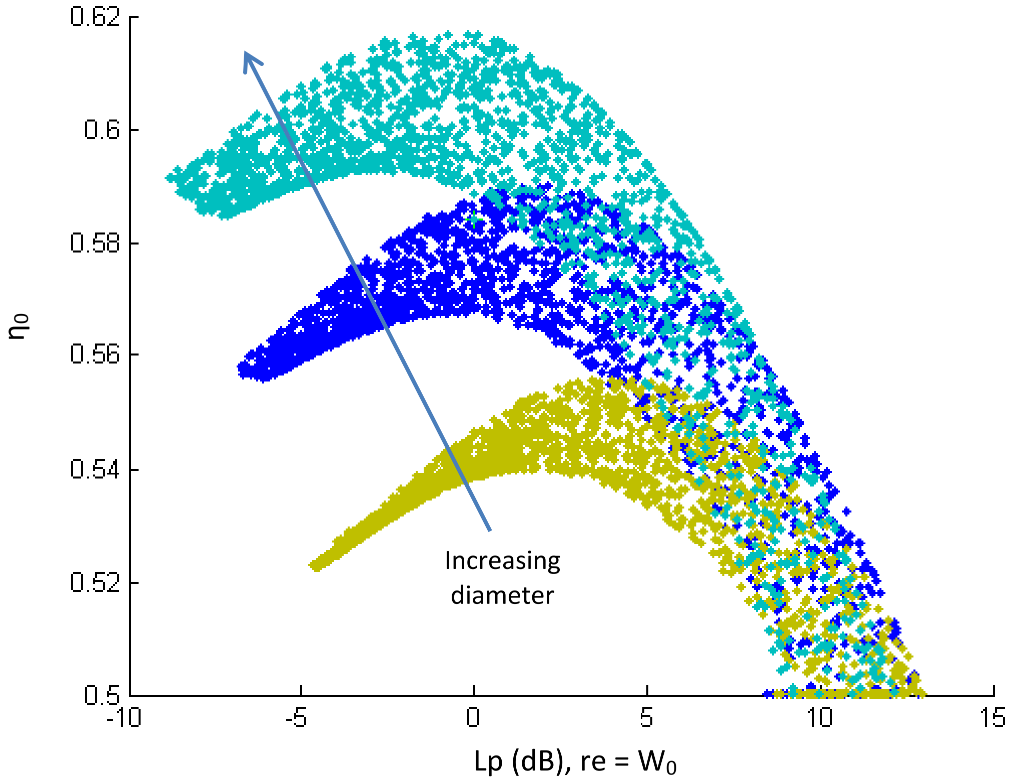

Figure 4: Efficiency against relative tip vortex noise for different diameter 4 bladed Wageningen propellers for the diameters 1.8m (mustard), 2.0m (blue) and 2.2m (teal)

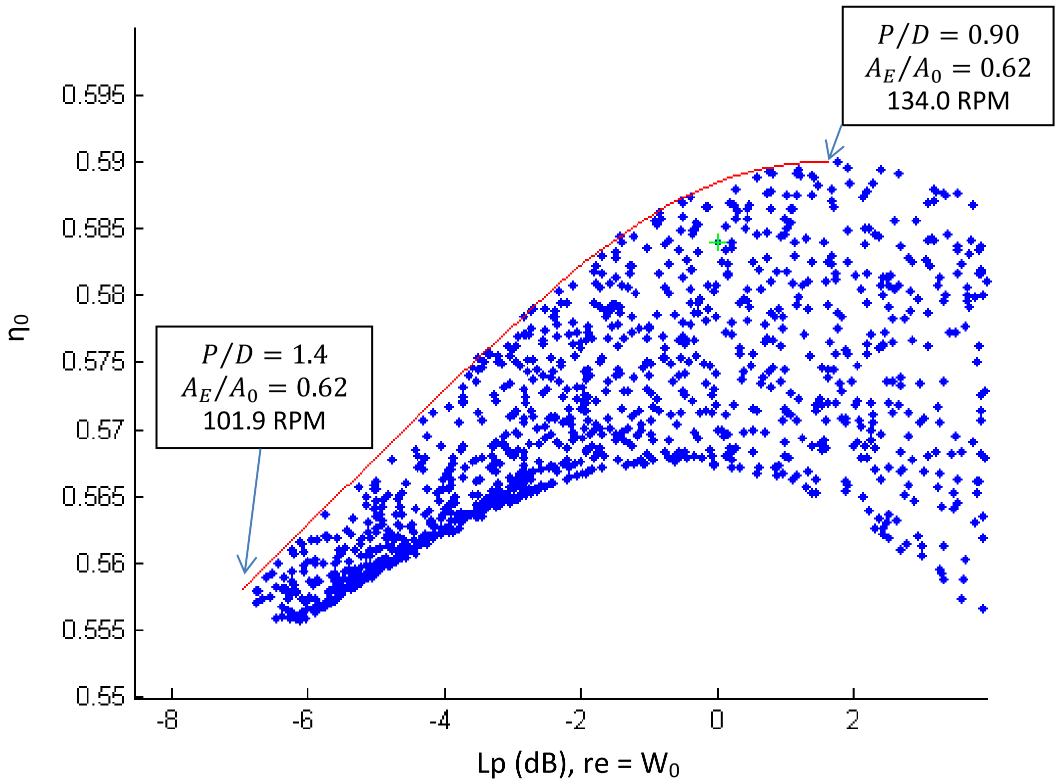

Figure 5: Efficiency against relative tip vortex noise for various 4 bladed, 2 m diameter Wageningen propellers with the Pareto-optimal front traced in red.

4. CONCLUSIONS

Propeller design is a complex task that must balance many different, sometimes conflicting, requirements and objectives. This paper has presented a methodology for exploring the trade-off space between maximising efficiency and minimising far-field noise. As a demonstration, the design of a Wageningen B series propeller was investigated for a candidate ship, with a simple tip-vortex spectrum level estimate used to assess noise. For the Wageningen B-Series, geometry variation was restricted to the choice of pitch-diameter ratio, blade-area ratio, diameter and number of blades. Performance characteristics were calculated from well-established polynomial expressions involving these parameters. The overarching constraint on the design was that it had to deliver the required thrust to propel the candidate ship at the desired operating speed. The Keller criterion was also applied to ensure candidate designs were less likely to cavitate. Even in this somewhat artificial scenario, the relationship between propeller efficiency and noise appears to be complicated. Even so, under the prescribed assumptions and chosen criteria, a clear trend emerged in our artificial scenario: that a larger, slower propeller offered better performance than a smaller, faster one delivering the same thrust. The framework may form the basis of an optimisation, parametric study, “what if” analysis or it could be used with more detailed derivations of propeller thrust and noise characteristics, at greater computational costs.

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