On ship powering predictions
and roughness allowances

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The present numerical exercise is complementing the paper with the same title.

Abstract

According to the rational theory of interaction the propulsive efficiency of a ship is obtained as product of the 'efficiency' of the hull-propeller configuration and of the hydraulic efficiency of the propeller, typically of value 0.8 .

The configuration efficiency depends on the frictional wake and resistance and on all 'additional' resistance components, normalised by the hull speed through the water and the area of the 'equivalent' propeller operating in the energy wake.

In order to arrive at the configuration efficiency, the energy wake, alias frictional wake, is estimated as function of the frictional momentum defect and the propeller loading, assuming that the equivalent propellers always digest the whole energy wakes.

Further the predicted jet power is determined and shown to be a linear function of the resistance component mentioned.

Normalised resistance values and energy wake fractions

At this stage eliminating the efficiency of the equivalent propeller results in the following function for the energy wake fraction depending on the normalised frictional and additional resistances

$$\mathrm{wake}(c_F, c_A, w) := \frac{2}{1+\sqrt{1+(c_F+c_A)\cdot(1-w)^{-2}}} - 2\cdot\frac{(1-w)\cdot w}{c_F}$$

Thus the following function permits to determine the values of the energy wake fraction depending on the values of the normalised resistances and subsequently the values of all magnitudes of interest.

```
resists(n) := | for i ∈ 0..n
              |   | c_RF[i] ← 0.15 + 0.02·i
              |   | for j ∈ 0..n
              |   |   | c_RA[j] ← 0.40 + 0.10·j
              |   |   | w ← 0.1
              |   |   | w_E[i,j] ← root(wake(c_RF[i], c_RA[j], w), w)
              | (c_RF  c_RA  w_E)
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Values determined

$n := 8$

$i := 0..n$ $\qquad$ $j := 0..n$

$(c_{RF} \;\; c_{RA} \;\; w_E) := \mathrm{resists}(n)$

$$c_{RF} = \begin{pmatrix} 0.150 \\ 0.170 \\ 0.190 \\ 0.210 \\ 0.230 \\ 0.250 \\ 0.270 \\ 0.290 \\ 0.310 \end{pmatrix} \qquad c_{RA} = \begin{pmatrix} 0.400 \\ 0.500 \\ 0.600 \\ 0.700 \\ 0.800 \\ 0.900 \\ 1.000 \\ 1.100 \\ 1.200 \end{pmatrix}$$

Energy wake fractions

$$w_E = \begin{pmatrix} 0.071 & 0.069 & 0.068 & 0.067 & 0.066 & 0.065 & 0.064 & 0.063 & 0.062 \\ 0.081 & 0.079 & 0.077 & 0.076 & 0.075 & 0.073 & 0.072 & 0.071 & 0.070 \\ 0.090 & 0.089 & 0.087 & 0.085 & 0.084 & 0.082 & 0.081 & 0.080 & 0.079 \\ 0.100 & 0.098 & 0.096 & 0.095 & 0.093 & 0.091 & 0.090 & 0.088 & 0.087 \\ 0.110 & 0.108 & 0.106 & 0.104 & 0.102 & 0.100 & 0.099 & 0.097 & 0.096 \\ 0.121 & 0.118 & 0.116 & 0.113 & 0.111 & 0.109 & 0.108 & 0.106 & 0.104 \\ 0.131 & 0.128 & 0.125 & 0.123 & 0.121 & 0.119 & 0.117 & 0.115 & 0.113 \\ 0.141 & 0.138 & 0.135 & 0.133 & 0.130 & 0.128 & 0.126 & 0.124 & 0.122 \\ 0.152 & 0.148 & 0.145 & 0.142 & 0.140 & 0.137 & 0.135 & 0.133 & 0.131 \end{pmatrix}$$

Hull influence ratios

$$\eta_{RQ_{i,j}} := \frac{1}{1 - w_{E_{i,j}}}$$

$$\eta_{RQ} = \begin{pmatrix} 1.076 & 1.075 & 1.073 & 1.072 & 1.070 & 1.069 & 1.068 & 1.067 & 1.066 \\ 1.088 & 1.086 & 1.084 & 1.082 & 1.081 & 1.079 & 1.078 & 1.077 & 1.075 \\ 1.099 & 1.097 & 1.095 & 1.093 & 1.091 & 1.090 & 1.088 & 1.087 & 1.085 \\ 1.112 & 1.109 & 1.107 & 1.104 & 1.102 & 1.100 & 1.099 & 1.097 & 1.095 \\ 1.124 & 1.121 & 1.119 & 1.116 & 1.114 & 1.112 & 1.110 & 1.108 & 1.106 \\ 1.137 & 1.134 & 1.131 & 1.128 & 1.125 & 1.123 & 1.121 & 1.118 & 1.116 \\ 1.151 & 1.147 & 1.143 & 1.140 & 1.137 & 1.135 & 1.132 & 1.130 & 1.127 \\ 1.164 & 1.160 & 1.156 & 1.153 & 1.150 & 1.147 & 1.144 & 1.141 & 1.139 \\ 1.179 & 1.174 & 1.170 & 1.166 & 1.162 & 1.159 & 1.156 & 1.153 & 1.150 \end{pmatrix}$$

Equivalent propeller efficiencies

$$\eta_{QJ_{i,j}} := \frac{2}{1+\sqrt{1+\left(c_{RF_i}+c_{RA_j}\right)\cdot\left(1-w_{E_{i,j}}\right)^{-2}}}$$

$$\eta_{QJ} = \begin{pmatrix} 0.877 & 0.861 & 0.846 & 0.831 & 0.818 & 0.805 & 0.794 & 0.782 & 0.772 \\ 0.872 & 0.855 & 0.840 & 0.826 & 0.813 & 0.800 & 0.789 & 0.778 & 0.767 \\ 0.866 & 0.850 & 0.835 & 0.821 & 0.808 & 0.795 & 0.784 & 0.773 & 0.762 \\ 0.860 & 0.844 & 0.829 & 0.815 & 0.802 & 0.790 & 0.779 & 0.768 & 0.757 \\ 0.855 & 0.839 & 0.824 & 0.810 & 0.797 & 0.785 & 0.774 & 0.763 & 0.752 \\ 0.849 & 0.833 & 0.818 & 0.804 & 0.792 & 0.780 & 0.768 & 0.758 & 0.748 \\ 0.843 & 0.827 & 0.812 & 0.799 & 0.786 & 0.774 & 0.763 & 0.753 & 0.742 \\ 0.836 & 0.821 & 0.806 & 0.793 & 0.781 & 0.769 & 0.758 & 0.747 & 0.737 \\ 0.830 & 0.815 & 0.801 & 0.787 & 0.775 & 0.763 & 0.752 & 0.742 & 0.732 \end{pmatrix}$$

Configuration efficiencies

$$\eta_{RJ_{i,j}} := \eta_{RQ_{i,j}}\cdot\eta_{QJ_{i,j}}$$

$$\eta_{RJ} = \begin{pmatrix} 0.944 & 0.925 & 0.907 & 0.891 & 0.875 & 0.861 & 0.847 & 0.835 & 0.822 \\ 0.948 & 0.929 & 0.911 & 0.894 & 0.878 & 0.864 & 0.850 & 0.837 & 0.825 \\ 0.952 & 0.933 & 0.914 & 0.897 & 0.882 & 0.867 & 0.853 & 0.840 & 0.827 \\ 0.957 & 0.936 & 0.918 & 0.901 & 0.885 & 0.870 & 0.855 & 0.842 & 0.830 \\ 0.961 & 0.940 & 0.921 & 0.904 & 0.888 & 0.872 & 0.858 & 0.845 & 0.832 \\ 0.965 & 0.944 & 0.925 & 0.907 & 0.891 & 0.875 & 0.861 & 0.847 & 0.835 \\ 0.969 & 0.948 & 0.929 & 0.911 & 0.894 & 0.878 & 0.864 & 0.850 & 0.837 \\ 0.974 & 0.952 & 0.933 & 0.914 & 0.897 & 0.882 & 0.867 & 0.853 & 0.840 \\ 0.978 & 0.957 & 0.936 & 0.918 & 0.901 & 0.885 & 0.870 & 0.855 & 0.842 \end{pmatrix}$$

Normalised jet power

$$c_{PJ_{i,j}} := \frac{\left(c_{RF_i} + c_{RA_j}\right)}{\eta_{RJ_{i,j}}}$$

$c_{PJ} =$

0.582	0.703	0.827	0.954	1.085	1.220	1.357	1.498	1.641
0.601	0.721	0.845	0.973	1.104	1.239	1.376	1.517	1.661
0.620	0.740	0.864	0.992	1.123	1.258	1.395	1.536	1.680
0.638	0.758	0.882	1.010	1.142	1.276	1.414	1.555	1.700
0.656	0.776	0.901	1.029	1.160	1.295	1.433	1.574	1.719
0.674	0.794	0.919	1.047	1.179	1.314	1.452	1.593	1.737
0.691	0.812	0.937	1.065	1.197	1.332	1.470	1.612	1.756
0.708	0.830	0.954	1.083	1.215	1.350	1.488	1.630	1.775
0.726	0.847	0.972	1.100	1.232	1.368	1.507	1.648	1.793

Linear approximation

$A_{(n+1)\cdot j+i,0} := 1$ $\quad A_{(n+1)\cdot j+i,1} := c_{RF_i}$ $\quad A_{(n+1)\cdot j+i,2} := c_{RA_j}$

$B_{(n+1)\cdot j+i} := c_{PJ_{i,j}}$

$X := \text{geninv}(A)\cdot B$

$$X = \begin{pmatrix} -0.10465 \\ 0.92084 \\ 1.32962 \end{pmatrix}$$

$a_0 := X_0$ $\quad a_F := X_1$ $\quad a_A := X_2$ $\quad a_{AF} := a_A - a_F$

$a_{AF} = 0.409$

Errors

$E := B - A\cdot X$ $\quad \text{stdev}(E) = 9.87 \times 10^{-3}$

$err_{i,j} := E_{(n+1)\cdot j+i}$

$err =$

0.017	0.004	−0.005	−0.010	−0.012	−0.011	−0.006	0.002	0.012
0.017	0.005	−0.004	−0.010	−0.011	−0.010	−0.005	0.003	0.014
0.017	0.005	−0.004	−0.009	−0.011	−0.009	−0.004	0.004	0.014
0.017	0.005	−0.004	−0.009	−0.011	−0.009	−0.004	0.004	0.015
0.017	0.004	−0.004	−0.009	−0.011	−0.009	−0.004	0.005	0.016
0.016	0.004	−0.005	−0.009	−0.011	−0.009	−0.003	0.005	0.016
0.015	0.003	−0.005	−0.010	−0.011	−0.009	−0.003	0.005	0.017
0.014	0.002	−0.006	−0.010	−0.011	−0.009	−0.004	0.005	0.017
0.013	0.001	−0.007	−0.011	−0.012	−0.010	−0.004	0.005	0.017

Practical rule of change

$$\Delta c_{PJ}(\Delta c_{RF}, \Delta c_{RA}) := a_F \cdot \Delta c_{RF} + a_A \cdot \Delta c_{RA}$$

Applications

Predictions compared

Traditional procedure

Predicting jet power for smooth hull, adding roughness allowance

$$c_{PJ.trad}(c_{PJ.0}, \Delta c_{RF}) := c_{PJ.0} + a_A \cdot \Delta c_{RF}$$

Rational procedure

Predicting jet power for rough hull based on jet power for smooth hull

$$c_{PJ.rat}(c_{PJ.0}, \Delta c_{RF}) := c_{PJ.0} + a_F \cdot \Delta c_{RF}$$

Difference in jet power predicted, traditionally over-estimated

$$\Delta c_{PJ.pred}(c_{RF.1.ship}, c_{RF.0.ship}) := a_{AF} \cdot (c_{RF.1.ship} - c_{RF.0.ship})$$

Model test procedure

The forgoing example assumes, that the configuration efficiencies for smooth full scale hulls are obtained computationally. If they are based on data acquired during model tests with external forces simulating 'frictional deduction', the situation is much more involved, values on model and full scale have to be distinguished.

In this case the only additional normalised forces accounted for are the normalised frictional deduction $c_{TF.mod}$ and the normalised wave resistance c_{RW}, the same on model and full scale according to Froude scaling. The resulting law for the configuration efficiency shows, that the crucial frictional term, dominant for large slow steaming ships, requires prior knowledge that is not available for new types of ships.

As shown in the basic paper, with the definition of the normalised frictional deduction

$$c_{TF.mod}(c_{RF.mod}, c_{RF.ship}) := c_{RF.mod} - c_{RF.ship}$$

the jet power for the smooth full scale hull is under-estimated and the total jet power may be under- or over-estimated according to the rule

$$\Delta c_{PJ.pred}(c_{RF.1.ship}, c_{RF.0.mod}) := a_{AF} \cdot (c_{RF.1.ship} - c_{RF.0.mod})$$

In case of over-estimation the allowance to cope with the systematic error counter-intuitively needs to be negative as before in case of the numerical prediction of the smooth hull frictional resistance.

Further numerical studies

Further numerical studies can readily be performed as soon as data become available.

Consequences

The first result demonstrates, that predicting the required powers for smooth hulls and crudely accounting for hull roughnesses over-estimates the configuration, thus counter-intuitively requiring 'negative' allowances to correct the systematic errors.

The second result demonstrates, that the traditional model technique, crudely applying the estimated frictional deductions as external forces, under-estimates the ship smooth hull jet powers required. In this case the total allowances to correct the systematic errors may be positive or negative.

The reason for the fundamental systematic differences is the fact, that the frictional resistances cannot correctly be treated as external forces.

Reference

The detailed exposition of the theory underlying this numerical exercise has been published in the '3rd, virtual INTERACTION 2017' on my website.

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