section 3.4 Resistance & Propulsion

source: Woud
Chapter 3

3.4.1 Hull Resistance

$R := c_1 \cdot v_s^2$ physics (3.1)

$P_E := R \cdot v_s$ $P_E = effective\_power$ defined (3.2)

$P_E \rightarrow c_1 \cdot v_s^3$ substitution (3.3)

$c_1 := y \cdot c_0(v_s)$ physics (3.4)

$y = f(fouling, displacement\_variations, sea\_state, water\_depth)$ essentially time and operations (3.5)

speed dependency of c_1 .... nondimensional resistance coefficient

$C_T := \dfrac{R}{\frac{1}{2} \cdot \rho \cdot A_s \cdot v_s^2}$ $C_T = non\_dimensional\_total\_resistance$ defined (3.6)

A_s (ship surface area) not readily available, so use volume proportionality ... A_s ~ Vol^2/3

$C_E := \dfrac{P_E}{\rho \cdot Vol^{\frac{2}{3}} \cdot v_s^3}$ $C_E = specific\_resistance$ defined (3.7)

since $\Delta = \rho \cdot Vol$ $Vol := \dfrac{\Delta}{\rho}$

$C_E := \dfrac{P_E}{\rho \cdot Vol^{\frac{2}{3}} \cdot v_s^3}$ $C_E \rightarrow \dfrac{P_E}{\rho \cdot \left(\frac{\Delta}{\rho}\right)^{\frac{2}{3}} \cdot v_s^3}$ $C_E := \dfrac{P_E}{\rho^{\frac{1}{3}} \cdot \Delta^{\frac{2}{3}} \cdot v_s^3}$ (3.8)

$C_E = f(Re, Fr, Ro, Hull\_form, external\_factors)$ dimensional analysis, physics (3.9)

$Re := \dfrac{\rho \cdot v_s \cdot Len}{\eta}$ $Re = reynolds\_number$ (3.10)

$Fr := \dfrac{v_s}{\sqrt{g \cdot Le}}$ $Fr = froude\_number$ (3.11)

$Ro := \dfrac{k}{Len}$ $Ro = non\_dimensional\_roughness$ defined (3.12)

$C_E = f(v_s, \Delta, fouling, Hull\_form, sea\_state, water\_depth)$

$P_E := R \cdot v_s$ $P_E \rightarrow c_1 \cdot v_s^3$ $c_1 := \dfrac{P_E}{v_s^3}$

and from (3.8) $P_E := \rho^{\frac{1}{3}} \cdot \Delta^{\frac{2}{3}} \cdot v_s^{3} \cdot C_E$ $c_1 := \frac{P_E}{v_s^{3}}$ $c_1 \rightarrow \rho^{\frac{1}{3}} \cdot \Delta^{\frac{2}{3}} \cdot C_E$ (3.13)

$P_E := \rho^{\frac{1}{3}} \cdot \Delta^{\frac{2}{3}} \cdot v_s^{3} \cdot C_E$ shows dependency of P_E on speed and displacement

e.g. if C_E and v_s are assumed constant ... a change in Δ from nominal changes effective power

$$P_E := \left(\frac{\Delta}{\Delta_{nom}}\right)^{\frac{2}{3}} \cdot P_{E\_nom} \qquad (3.14)$$

3.4.2 Propulsion

need to deliver thrust T to overcome resistance R at speed v_s $P_E := R \cdot v_s$ (3.2)

N.B. I am assuming one propeller. Woud uses k_p = number of propellers.

power delivered by propeller in water moving at v_A

$P_T := T \cdot v_A$ P_T = thrust_power defined (3.15)

Thrust deduction factor

required thrust T normally exceeds resistance R for two main reasons:
propulsor draws water along the hull and creates added resistance
conversely, the advance velocity is generally lower that the ship's speed, due to operating in the wake

t = thrust_reduction_factor = difference_between_thrust_and_resistance_relative_to_thrust defined

$t := \frac{T - R}{T}$ => $R := (1 - t) \cdot T$ $T := \frac{R}{1 - t}$ (3.16)

"The term *thrust deduction* was chosen because only part of the thrust produced by the propellers is used to overcome the pure towing resistance of the ship, the remaining part has to overcome the added resistance: so going from thrust T to resistance R there is a deduction. The term is somewhat misleading since starting from restance R the actual thrust T is increased." page 55

Wake fraction

propeller generally in boundary layer of ship where velocity is reduced; v_A is then < v_s

$w := \frac{v_s - v_A}{v_s}$ w = wake_fraction defined (3.17)

w = difference_between_ship_speed_and_advance_velocity_in_front_of_propeller_relative_to_v_s

"(Note that as a result of the suction of the propeller, the actual water velocity at the propeller entrance is much higher than the ship's speed: the *advance velocity*, however is equal to the water velocity at the propeller disc area if the propeller would not be present In other words it is the far field velocity that is felt by the propeller located in the boundary layer of the hull.)" page 56

thus ... $v_A := (1 - w) \cdot v_s$

Hull efficiency

with these two factors the thrust power does not equal the effective power. The ratio of effective power to thrust power is defined as the hull efficiency.

$$\eta_H := \frac{P_E}{P_T} \qquad (3.18)$$

redefine

$$T := \frac{R}{1-t} \qquad v_A := (1-w)\cdot v_s \qquad \eta_H := \frac{R\cdot v_s}{T\cdot v_A} \qquad \eta_H \rightarrow \frac{1-t}{1-w} \qquad (3.19)$$

Propeller efficiency

to deliver the required thrust at a certain ship's speed, power must be delivered to the propeller as torque Q and rotational speed ωp.

$$P_o := Q\cdot\omega_p \qquad \text{defined} \qquad P_o = \text{open\_water\_power} \qquad (3.20)$$

since ...

$$\omega_p := 2\cdot\pi\cdot n_p \qquad P_o := Q\cdot\omega_p \qquad P_o \rightarrow 2\cdot Q\cdot\pi\cdot n_p$$

$$\eta_o := \frac{P_T}{P_o} \qquad \text{defined} \qquad \eta_o = \text{open\_water\_efficiency} \qquad \eta_o \rightarrow \frac{1}{2}\cdot T\cdot\frac{v_A}{Q\cdot\pi\cdot n_p} \qquad (3.21)$$

"In reality, i.e. behind the ship, the torque M_p and thus the power delivered Pp actually delivered to the propeller are slightly different as a result of the non-uniform velocity field in front of the propeller." page 58

PNA vol II page 135 says: " Behind the hull, at the same effective speed of advance V_A, the thrust T and revolutions n will be associated with some different torque Q, and the efficiency behind the hull will be $\eta_B := \frac{T\cdot V_A}{2\cdot\pi\cdot n\cdot Q}$ (34)

The ratio of behind to open efficiencies under these conditions is called the relative rotative efficiency, being given by

$$\eta_B := \frac{T\cdot V_A}{2\cdot\pi\cdot n\cdot Q} \qquad \eta_o := \frac{T\cdot V_A}{2\cdot\pi\cdot n\cdot Q_o} \qquad \eta_R := \frac{\eta_B}{\eta_o} \qquad \eta_R \rightarrow \frac{1}{Q}\cdot Q_o \qquad (35)$$

Thus we define P_p as power delivered. (per propeller)

$$P_p := M_p\cdot\omega_p \qquad P_p \rightarrow 2\cdot M_p\cdot\pi\cdot n_p \qquad (3.22)$$

and ... the ratio between open water power and actually delivered power is

$$\eta_R := \frac{P_o}{P_p} \qquad \eta_R \rightarrow \frac{Q}{M_p} \qquad (3.23)$$

Propulsive efficiency

combining all these effects .. looking forward to design/evaluation at model (open water) scale

$$\eta_D := \frac{P_E}{P_D} \qquad \text{defined} \qquad \eta_D = \frac{\text{effective\_power}}{\text{power\_delivered}} = \frac{P_E}{P_p} \qquad \text{for } k_p = 1 \qquad (3.24)$$

rewriting ...

$$\eta_D = \frac{P_E}{P_p}\cdot\frac{P_T}{P_T}\cdot\frac{P_o}{P_o} = \frac{P_E}{P_T}\cdot\frac{P_T}{P_o}\cdot\frac{P_o}{P_p}$$

using definitions of efficiency from above ...

$$\eta_H = \frac{P_E}{P_T} = \frac{1-t}{1-w} \qquad \eta_o := \frac{P_T}{P_o} \qquad \eta_R := \frac{P_o}{P_p} \qquad \eta_D := \eta_H\cdot\eta_o\cdot\eta_R \qquad \eta_D := \frac{1-t}{1-w}\cdot\eta_o\cdot\eta_R$$

(3.25) (3.26)