0.1 Thruster dynamics

This section is based on **?**, and **?**. Please see these references for more in-depth analysis of thruster control, especially other control strategies such as torque control, and combined torque and power control. Only speed control will be covered in the following, both because this is the most common strategy, and because it is the algorithm used for thruster control at Gunnerus (REF KM).

Thruster control is an important aspect, and good control algorithms can save fuel, and wear and tear of the equipment. Based on the force demand calculated from the high level DP controller, or from manual control, the thrust allocation distributes the force demand to each thruster. Based on the required force given by the thrust allocation, the low level thruster controller calculates the desired shaft speed of the propeller (based on some mapping to be discussed later). Other possible control strategies include torque control, and power control.

The low level thruster control scheme consists of five main components (**?**). There is a reference generator to ensure physically feasible input, a core controller (feedback controller), a friction feedforward term, a intertia feedforward term, and a torque saturation block to limit the commanded torque within allowed (and physical) limits. This commaned torque, Q_c is fed into the electric motor, and the motor dynamics can be modelled as a first order model such as

$$\dot{Q}_m = \frac{1}{T_m}(Q_m - Q_c), \tag{1}$$

where Q_m, Q_c, and T_m are the actual motor torque, the commanded motor torque, and the first order time constant for the motor dynamics, respectively. The shaft dynamics is given as

$$I_s\dot{\omega} = Q_m - Q_a - K_\omega \omega, \tag{2}$$

where I_s, Q_a, K_ω, and ω are the shaft inertia, the propeller load torque, the friction coefficient, and the shaft speed respectively. Finally, hydrodynamic loss effects will affect the delivered thrust. The thrust force actually delivered after losses have been accounted for is called the actual thrust T_a. For a DP vessel typical loss effects are (**?**)

- in-line velocity fluctuations,
- cross-coupling drag,
- Coanda effect,
- ventilation,
- in-and-out-of-water-effects,
- thruster-thruster interaction.

For R/V Gunnerus ventilation is only a problem in rough weather when the propellers comes close to the surface, and similarly for in-and-out-of-water-effects (really bad weather).

The tunnel thruster is only effective for low-speed, and will become inefficient at higher speed due to cross-coupling drag.

The relationship between actual thrust force $T_a[N]$ and actual torque $Q_a[Nm]$, with the shaft speed of the thruster are given by

$$T_a = sign(n)\rho K_T D^4 n^2, \tag{3}$$

$$Q_a = sign(n)\rho K_Q D^5 n^2, \tag{4}$$

where $n[\frac{1}{s}]$ is the shaft speed, $\rho[\frac{kg}{m^3}]$ is the water density, $D[m]$ the propeller diameter, and $K_T[-] > 0$, and $K_Q[-] > 0$ are the thrust and torque coefficients, respectively. Values for K_T and K_Q are found from open water tests. Both coefficients are a function of a number of parameters, the advance ratio, the expanded blade area (ratio), the pitch ratio, and the number of blades. For Q_a the Reynold number and the maximum thickness of the blade with respect to the chord length is also of importance. The advance ratio J_a is given as

$$J_a = \frac{V_a}{nD}, \tag{5}$$

where V_a is the inflow velocity on the propeller.

The power consumption can be found from (**?**)

$$P_a = 2\pi n Q_a = sign(n)2\pi K_Q \rho D^5 n^3. \tag{6}$$

0.1.1 Simplified model

According to **?**, full scale experiments have shown that the thruster dynamics can be modelled as a first order process with quite satisfactory results. This gives the thruster dynamics as

$$\dot{T}_m = -A_{thr}^{-1}(T_m - T_c) \tag{7}$$

where T_m and T_c are obtained and commanded thrust, respectively. $A_{thr} \in \mathbb{R}^{3\times 3}$ is a diagonal matrix containing the time constants for the thrust in surge, sway, and yaw direction, respectively. This model is applicable for the step test analysis, and will be used in the system identification process.

0.1.2 Thrust allocation

The DP controller (or manual control by levers) calculates desired force and moment to be applied in surge, sway, and yaw. Thrust allocation is the process of distributing this force demand on the thrusters of the vessel, and the low level thruster controller map this to a desired shaft speed of the individual thrusters (**?**). In the case of an overactuated vessel, the thrust allocation problem becomes an optimization problem. Most DP vessels are overactuated. Generally, the thrust force is written as (**?**)

$$\boldsymbol{\tau} = \boldsymbol{T}(\boldsymbol{\beta})\boldsymbol{K}\boldsymbol{u}, \tag{8}$$

where $\boldsymbol{\beta}$ is a vector of the azimuth angles. Let n be the number of DOF's, and r be the number of thruster, then the thrust configuration matrix $\boldsymbol{T}(\boldsymbol{\beta}) \in \mathbb{R}^{n\times r}$ geometrically describes the thruster position and their orientation with respect to the centre of rotation. The matrix $\boldsymbol{K} \in \mathbb{R}^{r\times r}$ is a diagonal matrix containing the thrust coefficients. For speed controlled thrusters, $\boldsymbol{K}$ and $\boldsymbol{u} \in \mathbb{R}^r$ are given as

$$\begin{aligned}\boldsymbol{K} &= diag\{k_1, \quad k_2, \quad \cdots, \quad k_r\} \\ &= diag\{\rho K_{T1} D_1^4, \quad \rho K_{T2} D_2^4, \quad \cdots, \quad \rho K_{Tr} D_r^4\},\end{aligned} \tag{9}$$

$$u = \begin{bmatrix} |n_1|n_1 \\ |n_2|n_2 \\ \cdots \\ |n_r|n_r \end{bmatrix}. \tag{10}$$

For R/V Gunnerus (before retrofit), there are two main fixed pitch propellers (**?**) with rudder in the stern, and a tunnel thruster in the bow (no azimuth thrusters). Given the following definitions

$$u_1 : \text{port main propeller} \tag{11}$$

$$u_2 : \text{starboard main propeller} \tag{12}$$

$$u_3 : \text{tunnel thruster, bow,} \tag{13}$$

and let l_1, l_1 and l_3 be the moment arms in yaw for u_1, u_2 and u_3, respectively. For $F_1 = k_1 u_1$, $F_2 = k_2 u_2$, and $F_3 = k_3 u_3$, the thrust configuration is shown in Figure 1.

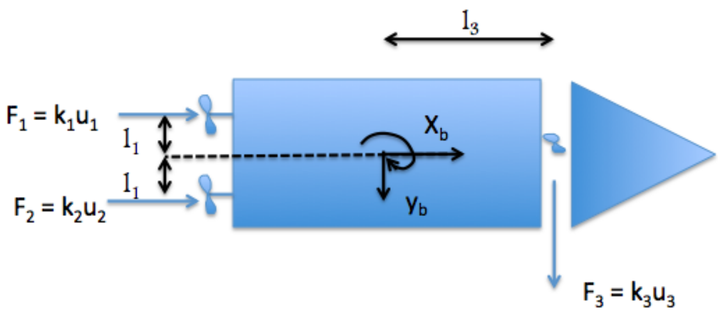

Figure 1: Thruster configuration, Gunnerus - before retrofit (bow to the right)

Be defining the rudder angles $\boldsymbol{\alpha}$ as

$$\boldsymbol{\alpha} = \begin{bmatrix}\alpha_1 & \alpha_2\end{bmatrix}^T \in \mathbb{R}^2, \tag{14}$$

where α_1 and α_2 are the rudder angles of the port and starboard rudder, respectively, the thrust configuration matrix is written as

$$\boldsymbol{T} = \begin{bmatrix} b_{11}(\alpha) & b_{12}(\alpha) & 0 \\ b_{21}(\alpha) & b_{22}(\alpha) & 1 \\ b_{31}(\alpha)l_1 & b_{32}(\alpha)(-l_1) & -l_3 \end{bmatrix}. \tag{15}$$

If the surge speed is small, and the tunnel thruster is active, the yaw motion will not depend linearly on the rudder angle as in the sway-yaw subsystem of Section **??**.