Note on the Body Force Propeller implementation

Theory

In FINE^{TM}/Marine, the momentum equations include a body-force term $\mathbf{f_b}$, used to model the effects of a propeller without modeling the real propeller. There are numerous approaches for calculating $\mathbf{f_b}$ including simple prescribed distributions, which recover the total thrust **T** and torque **Q**, to more sophisticated methods which use a propeller performance code in an interactive way with the RANS solver to capture propeller-hull interaction and to distribute $\mathbf{f_b}$ according to the actual blade loading. For the latter, special interface should be developed to extract effective wake from RANS solution and to produce $\mathbf{f_b}$ calculated by a propeller performance code. FINE^{TM}/Marine does, however, include a prescribed body force with axial and tangential components. The radial distribution of forces, with components f_{bx} (axial), f_{br} (radial)=0 and $f_{b\theta}$ (tangential), is based on non-iterative calculation of Stern et al.(1), the Hough and Ordway(2) circulation distribution with optimum type from Goldstein(3), and without any loading at the root and tip:

$$f_{bx}=A_x r^* \sqrt{1-r^*}, \quad f_{b\theta}=A_\theta \frac{r^*\sqrt{1-r^*}}{r^*(1-r_h')+r_h'}$$

They represent body forces per unit volume normalized by $\rho U^2/L$ where U is the reference velocity, L is a reference length, and ρ the fluid density. Coefficients are expressed as:

$$r^*=\frac{r'-r_h'}{1-r_h'}, \quad r_h'=R_H/R_P, \quad r'=r/R_P$$

$$r=\sqrt{(y-Y_{PC})^2+(z-Z_{PC})^2}$$

$$A_x=\frac{C_T}{\Delta}\frac{105}{16(4+3r_h')(1-r_h')}$$

$$A_\theta=\frac{K_Q}{\Delta J^2}\frac{105}{\pi(4+3r_h')(1-r_h')}$$

$$J=\frac{2\pi U}{\Omega D_P}=\frac{U}{nD_P}, \quad D_P=2R_P, \quad n=\Omega/2\pi$$

$$C_T=\frac{2T}{\rho U^2 \pi R_P^2}, \quad K_T=\frac{T}{\rho n^2 D_P^4}, \quad K_Q=\frac{Q}{\rho n^2 D_P^5}$$

and where C_T and K_Q are the thrust and torque coefficients, J is the advance coefficient, n is the number of rotations per second (rps), Ω is the rotation speed, R_P is the propeller radius, R_H is the hub radius, Δ is the mean chord length projected into the x-z plane (or actuator disk thickness), and Y_{PC} and Z_{PC} define the propeller center coordinates. As derived, these forces are defined over an "actuator cylinder" with volume defined by R_P, R_H, and Δ.

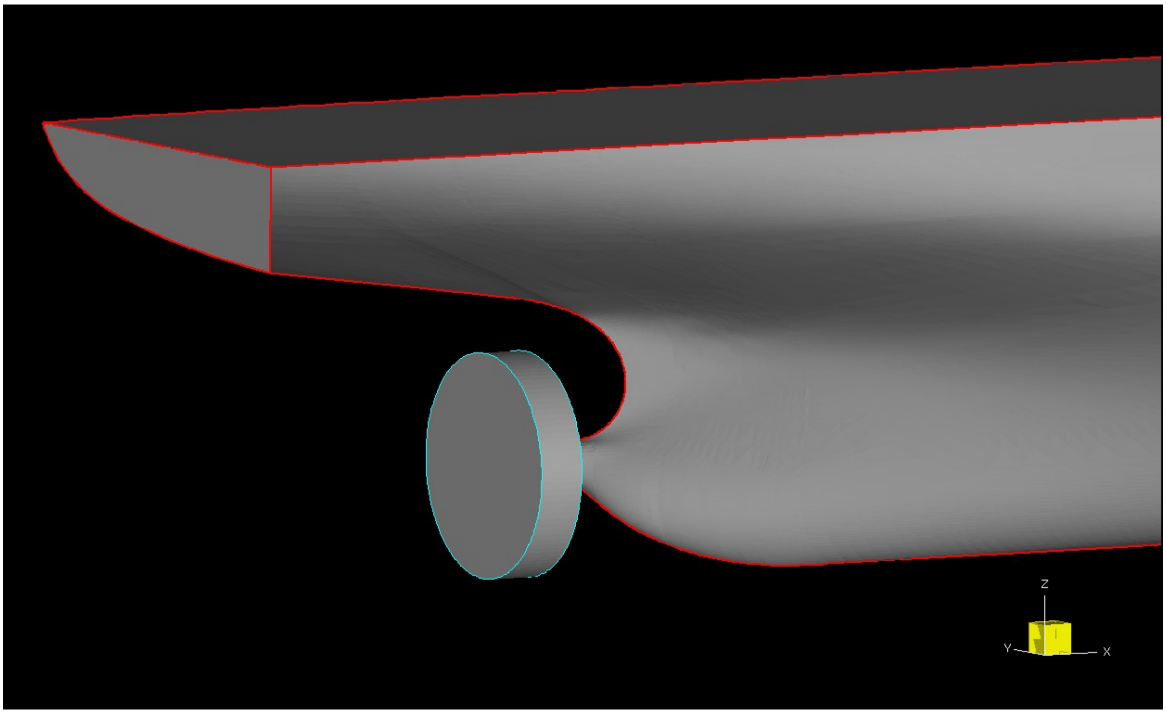
Integration of the body forces over this analytical volume exactly recovers the prescribed thrust **T** and torque **Q**:

$$T=\rho L^2 U^2 \iiint_A f_{bx} dA$$
$$Q=\rho L^3 U^2 \iiint_A r f_{b\theta} dA$$
$$dA=2\pi r \Delta dr$$

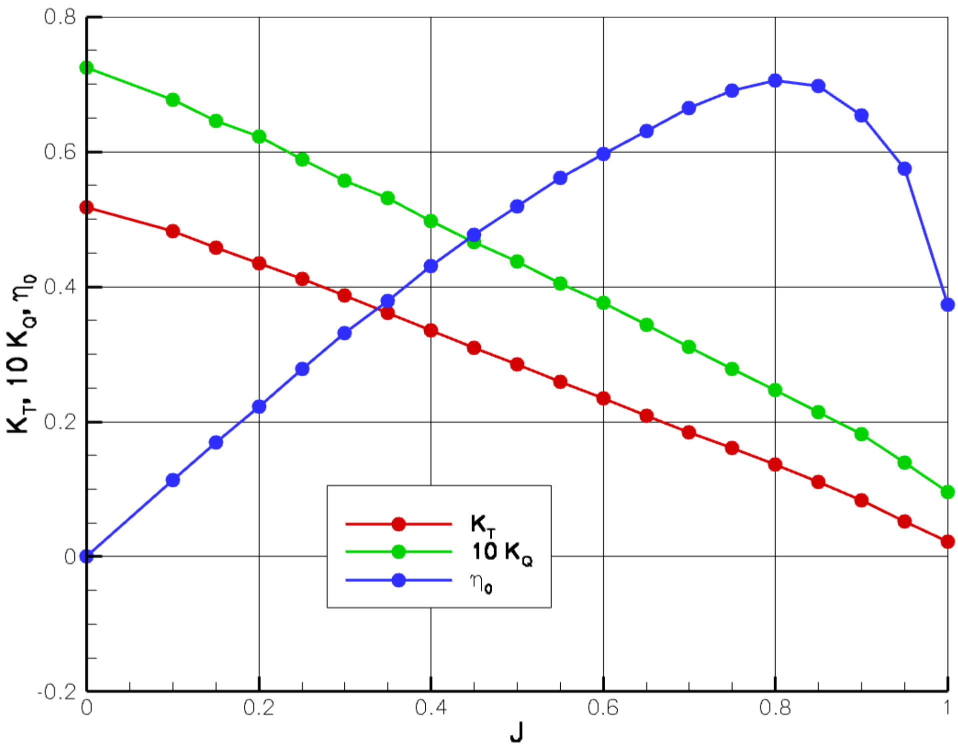
Practice

In FINE™/Marine, user does not explicitly need to specify C_T, K_Q and J, but prescribes the thrust **T** and the torque **Q**. A_x and A_θ coefficients are then computed using the above relations.

As an example, a fictitious propeller region is materialized below where body force method must be activated:



If the propeller torque **Q** is not known, it is however possible to estimate its magnitude from open water test of the propeller, if available. Such open water test usually provides the performance curve as illustrated for the propeller of the KRISO Container Ship (KCS) from the test case 2 of the Tokyo Workshop 2005:



For a prescribed thrust and/or an advance ratio parameter knowing the advance speed U and ratio J from the propeller rotation speed (n or Ω), K_Q is obtained form the performance curve and the propeller torque **Q** can be deduced from the propeller thrust **T** as:

$$\boldsymbol{Q} = \boldsymbol{T} D_P \frac{K_Q}{K_T}$$

As an example, for this case, the propeller condition was D_P=0.25m and J=0.732. From the performance curve, we have K_T=0.170 and K_Q=0.029 so the previous relation writes **Q ~ 1.47 T**.

References

(1) Stern, F., Kim, H.T., Patel, V.C., and Chen, H.C., "A Viscous-Flow Approach to the Computation of Propeller-Hull Interaction," Journal of Ship Research, Vol. 32, No. 4, December 1988, pp. 246-262.
(2) Hough, G. and Ordway, D., “The Generalized Actuator Disk,” Technical Report TAR-TR 6401, Therm Advanced Research, Inc., 1964.
(3) Goldstein, S., "On the Vortex Theory of Screw Propellers", Proc. of the Royal Society (A) 123, 440, 1929.