MARITIME

SHOPERA Workshop WP2&4:

Simple Semi-Empirical Models for X_R- & Y_R-Rudder Forces

Duisburg, 2015-03-16&17

Vladimir SHIGUNOV

2015-03-16&17

[15 min]

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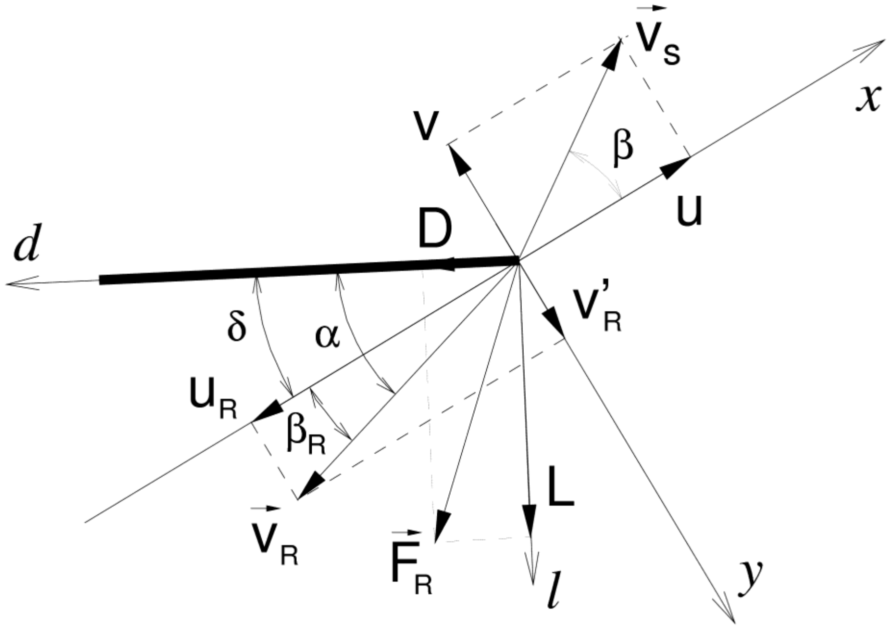
Rudder Forces

Forces on the rudder

$$X_R = -L\sin(\alpha-\delta) - D\cos(\alpha-\delta)$$

$$Y_R = L\cos(\alpha-\delta) - D\sin(\alpha-\delta)$$

$$N_R = -Y_R l_R$$



X_R longitudinal force, Y_R lateral force, L lift, D drag, α angle of attack with respect to surrounding flow, δ rudder angle, $l_R(=L_{pp}/2)$ lever of lateral rudder force

The lift and drag on the rudder are calculated as

$$L = C_L(\underline{\alpha})\frac{\rho}{2}\underline{v_R^2}A_R \qquad D = C_D(\underline{\alpha})\frac{\rho}{2}\underline{v_R^2}A_R$$

→ $C_L(\alpha), C_D(\alpha)$: empirical formulae
α, v_R: model is required

A_R is submerged projected rudder area, v_R is the average flow speed on the rudder

Rudder behind Working Propeller: Söding Model (Brix, 1993)

J. Brix, Manoeuvring Technical Manual, Seehafen Verlag 1993

(1) nominal inflow to the propeller

$$u_a = u(1 - w)$$

(2) propeller loading coefficient (T = propeller thrust, u_a advance speed of propeller, A_P propeller disc area)

$$C_{Th} = T \Big/ \left(0.5 \rho u_a^2 A_P\right)$$

(3) mean axial speed far behind propeller (Rankine method)

$$u_\infty = u_a \sqrt{1 + C_{Th}}$$

(4) corresponding slipstream radius (R_P=D_P/2 is the propeller radius)

$$r_\infty = R_P \sqrt{0.5\left(1 + u_a / u_\infty\right)}$$

(5) slipstream radius at the rudder (x = distance from propeller plane to COG of rudder area in propeller slipstream)

$$r = R_P \frac{0.14\left(r_\infty / R_P\right)^3 + \left(r_\infty / R_P\right)\left(x / R_P\right)^{3/2}}{0.14\left(r_\infty / R_P\right)^3 + \left(x / R_P\right)^{3/2}}$$

(6) corresponding average axial velocity at the rudder in the propeller slipstream

$$u_x = u_\infty \left(r_\infty / r\right)^2$$

„non-standard“

Rudder behind Working Propeller: Söding Model (Brix, 1993) (2)

„non-standard"

(7) increase of slipstream radius to take into account turbulent mixing in the propeller race

$$\Delta r = 0.15x\left(u_x - u_a\right)/\left(u_x + u_a\right)$$

(8) corresponding average slipstream speed

$$u_{\mathrm{corr}} = u_a + \left(u_x - u_a\right)\left(\frac{r}{r + \Delta r}\right)^2$$

(9) mean squared longitudinal velocity on the rudder (A_R rudder area, $A_R{}^s$ rudder area within propeller slipstream)

$$\overline{u^2} = \left(1 - A_R^s / A_R\right)u_a^2 + \left(A_R^s / A_R\right)u_{\mathrm{corr}}^2$$

(10) transverse flow speed on the rudder ($v=-v_s\sin\beta$ is drift speed of the ship)

$$v' = -\kappa v, \qquad \left[\kappa = 0.36\right]$$

(11) angle of attack of the flow on rudder

$$\alpha = \delta + \mathrm{tg}^{-1}\left(v'/\sqrt{\overline{u^2}}\right)$$

(12) total flow speed on rudder

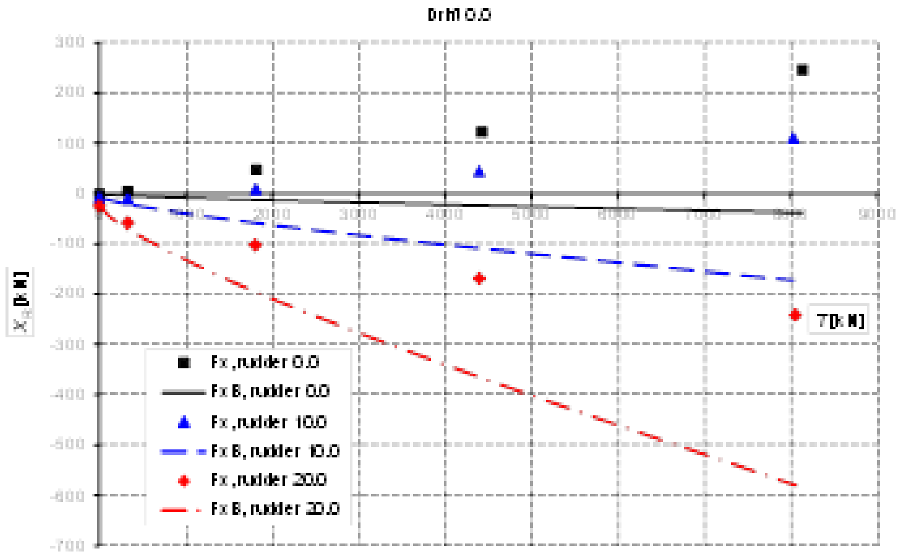
$$v_R = \left[\overline{u^2} + \left(v'\right)^2\right]^{1/2}$$

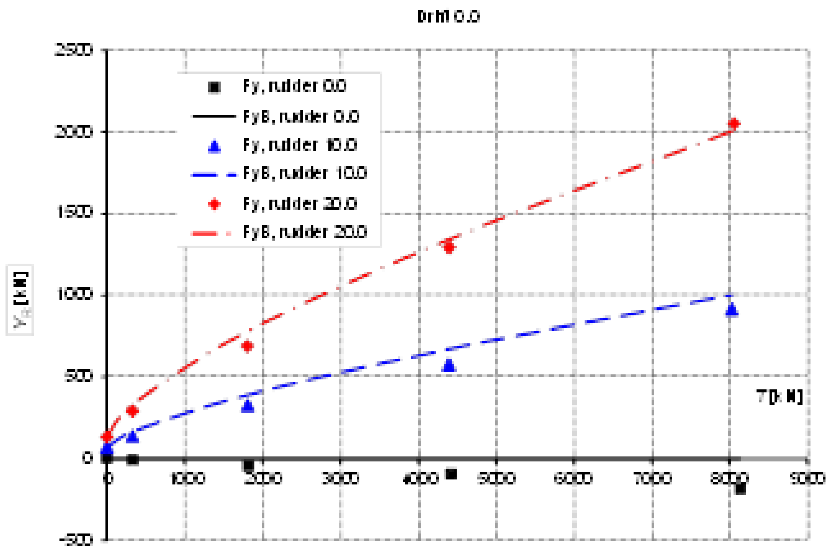
(13) correction for finite breadth of propeller slipstream

$$L^* = L \cdot \left(u_a / u_{\mathrm{corr}}\right)^f, \quad f = 2\left(\frac{2c}{2c + r + \Delta r}\right)^8$$

„non-standard"

Rudder behind Working Propeller: Söding Model (Brix, 1993) (3)





- The model is rather Level 2 model – seems too complex for Level 1
- Agreement of lateral force is very good
- Longitudinal force X_R is over-estimated (thrust effect of twisted rudder not accounted for)
- Note that for twisted rudders, sufficient model test data will always be available – in Level 1 and Level 2 methods, thrust due to twisted rudder does not need to be taken into account
- GL is working on empirical formula for thrust on rudder

Simplifications

Simplification 1 of Söding Model (Brix, 1993)

(1) nominal inflow to the propeller

$$u_{\mathrm{a}} = u\left(1 - w\right)$$

(2) propeller loading coefficient (*T* = propeller thrust, u_{a} advance speed of propeller, A_{P} propeller disc area)

$$C_{\mathrm{Th}} = T \Big/ \left(0.5 \rho u_{\mathrm{a}}^{2} A_{\mathrm{P}}\right)$$

(3) mean axial speed far behind propeller (Rankine method)

$$u_{\infty} = u_{\mathrm{a}} \sqrt{1 + C_{\mathrm{Th}}}$$

(4) corresponding slipstream radius ($R_{\mathrm{P}}=D_{\mathrm{P}}/2$ is the propeller radius)

$$r_{\infty} = R_{\mathrm{P}} \sqrt{0.5\left(1 + u_{\mathrm{a}} / u_{\infty}\right)}$$

(5) slipstream radius at the rudder (*x* = distance from propeller plane to COG of rudder area in propeller slipstream)

$$r = R_{\mathrm{P}} \frac{0.14\left(r_{\infty} / R_{\mathrm{P}}\right)^{3} + \left(r_{\infty} / R_{\mathrm{P}}\right)\left(x / R_{\mathrm{P}}\right)^{3/2}}{0.14\left(r_{\infty} / R_{\mathrm{P}}\right)^{3} + \left(x / R_{\mathrm{P}}\right)^{3/2}}$$

(6) average axial velocity at the rudder in the propeller slipstream

$$u_{\mathrm{x}} = u_{\infty}\left(r_{\infty} / r\right)^{2}$$

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Simplification 1 of Söding Model (Brix, 1993) (2)

(7) increase of slipstream radius to take into account turbulent mixing in the propeller race

$$\Delta r = 0.15x\left(u_x - u_a\right)\big/\left(u_x + u_a\right)$$

(8) corresponding average slipstream speed

$$u_{\mathrm{corr}} = u_a + \left(u_x - u_a\right)\left(\frac{r}{r+\Delta r}\right)^2$$

(9) mean squared longitudinal velocity on the rudder (A_R rudder area, A_R^s rudder area within propeller slipstream)

$$\overline{u^2} = \left(1 - A_R^s\big/A_R\right)u_a^2 + \left(A_R^s\big/A_R\right)u_{\mathrm{corr}}^2$$

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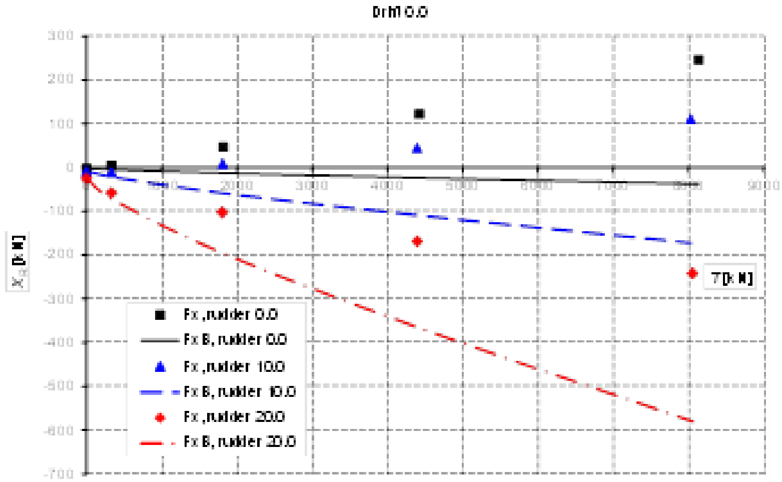
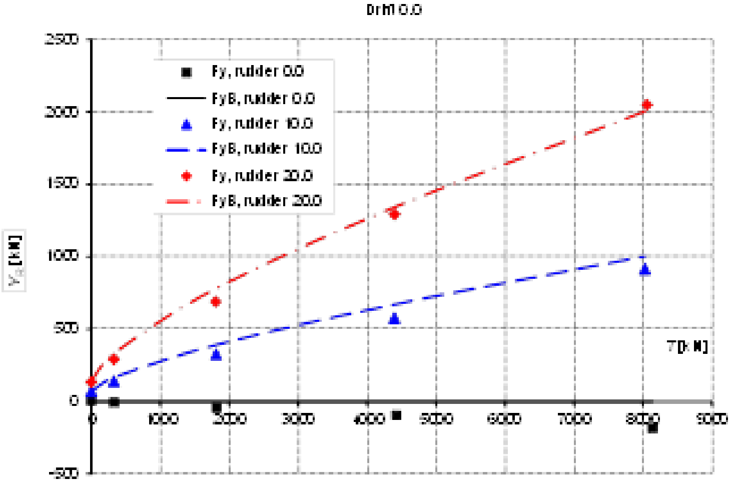
(13) correction for finite breadth of propeller slipstream

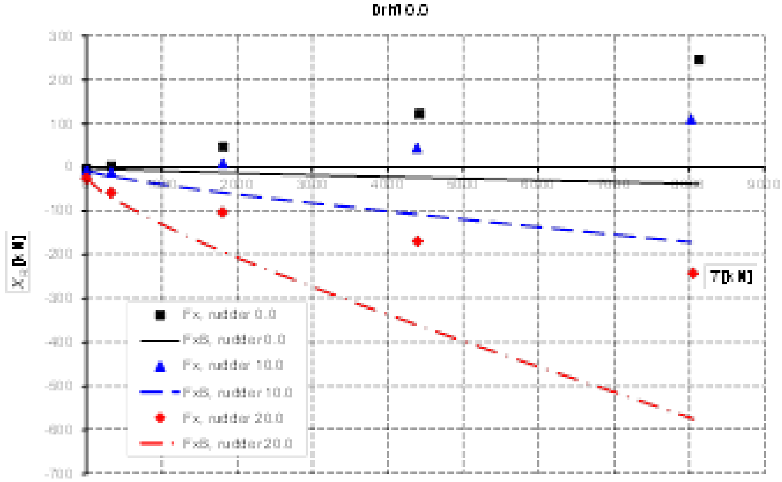
$$\xcancel{L^* = L\cdot\left(u_a/u_{\mathrm{corr}}\right)^f, \quad f = 2\left(\frac{2c}{2c+r+\Delta r}\right)^8}$$

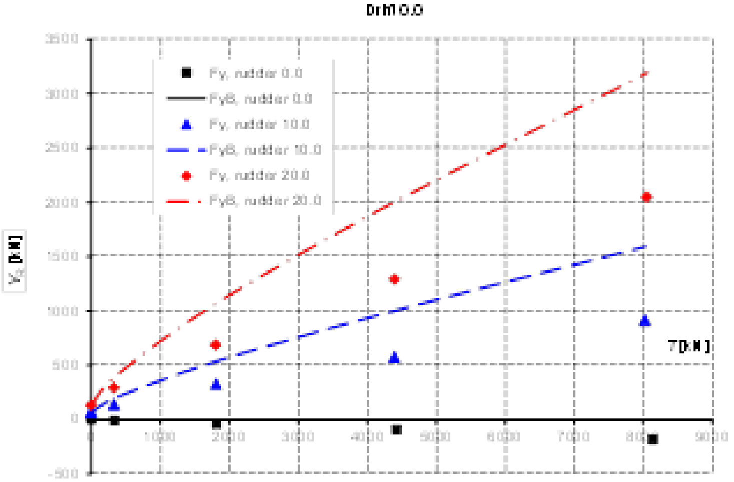
Simplification 1 of Söding Model (Brix, 1993) (3)





original model





simplified model

=> not conservative

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Simplification 2 of Söding Model (Brix, 1993)

(1) nominal inflow to the propeller

$$u_{\mathrm{a}} = u\left(1 - w\right)$$

(2) propeller loading coefficient (*T* = propeller thrust, u_{a} advance speed of propeller, A_{P} propeller disc area)

$$C_{\mathrm{Th}} = T\Big/\left(0.5\rho u_{\mathrm{a}}^{2} A_{\mathrm{P}}\right)$$

(3) mean axial speed far behind propeller (Rankine method)

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(6) average axial velocity at the rudder in the propeller slipstream

$$u_{\mathrm{x}} = u_{\infty}\left(r_{\infty}/r\right)^{2}$$

Simplification 2 of Söding Model (Brix, 1993) (2)

(7) increase of slipstream radius to take into account turbulent mixing in the propeller race

$$\Delta r = 0.15x\left(u_x - u_a\right)/\left(u_x + u_a\right)$$

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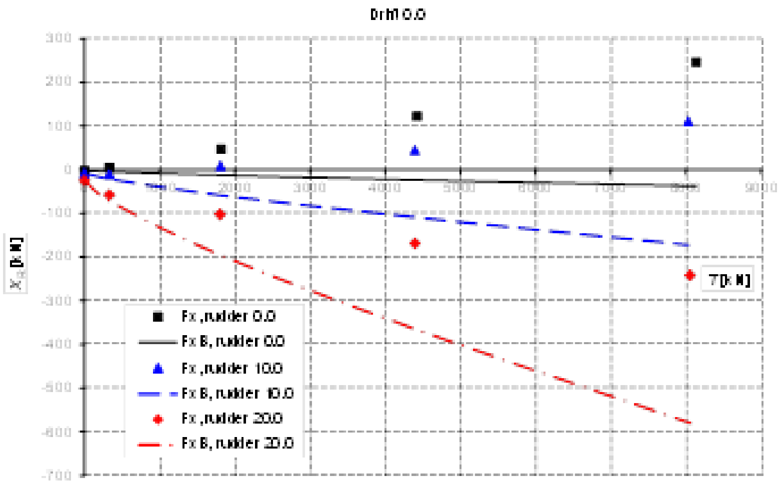
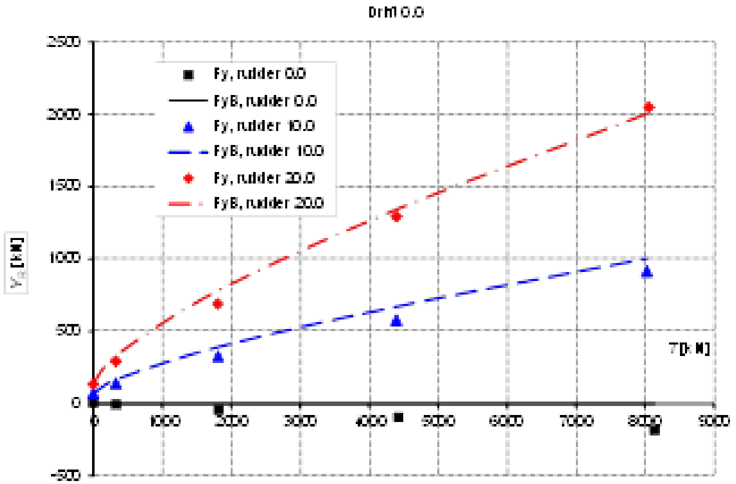
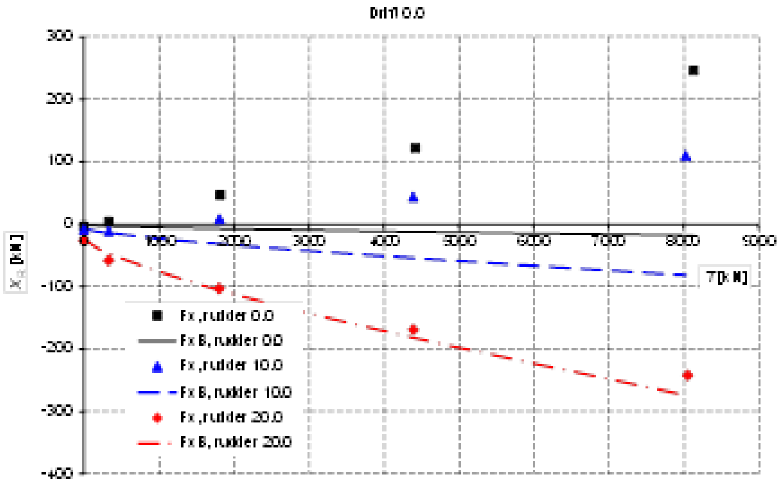
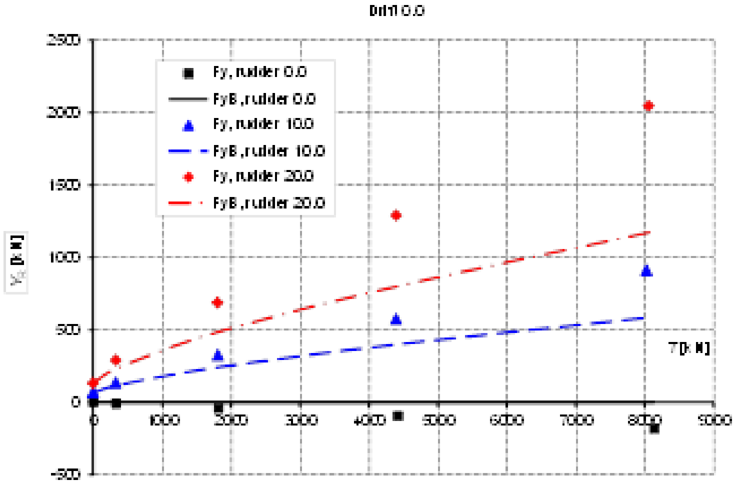




original model





simplified model

=> too conservative

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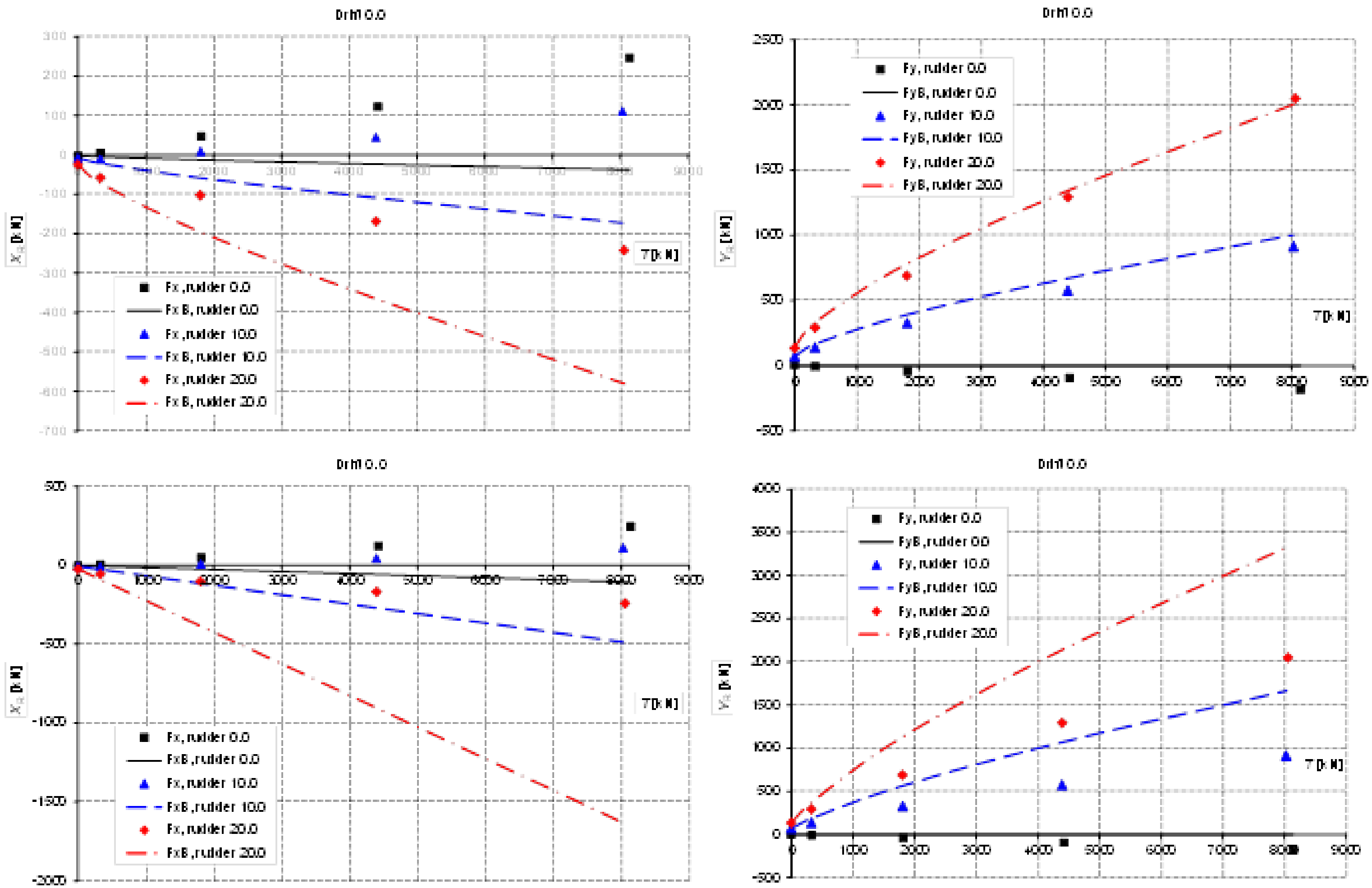

original model

simplified model

=> not conservative

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(6) average axial velocity at the rudder in the propeller slipstream

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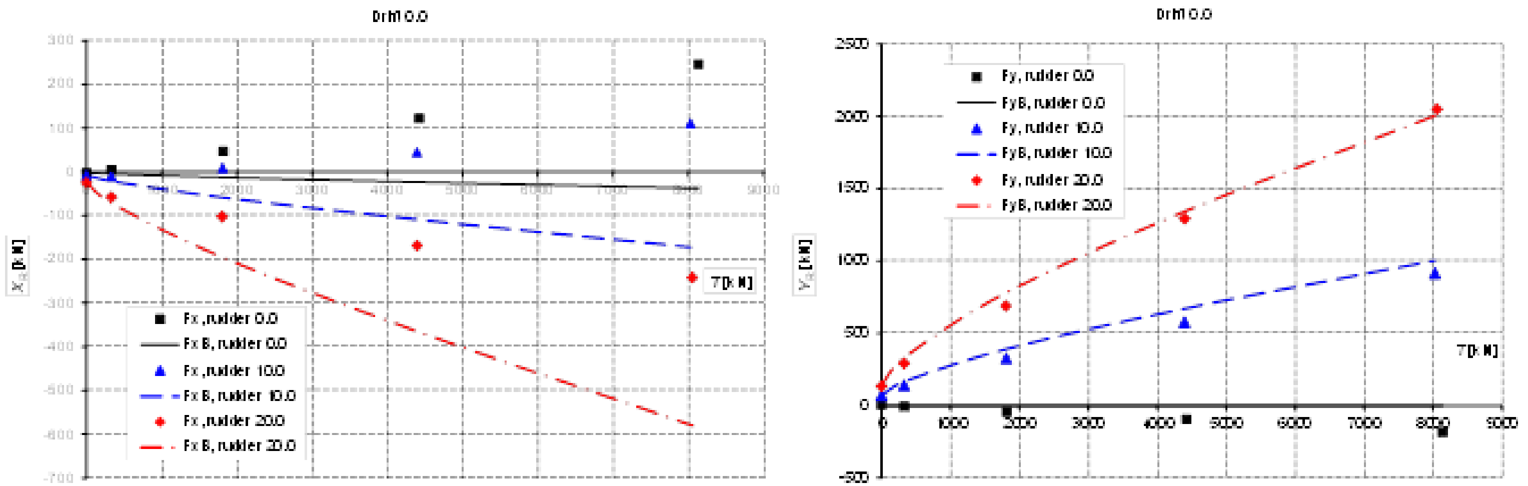
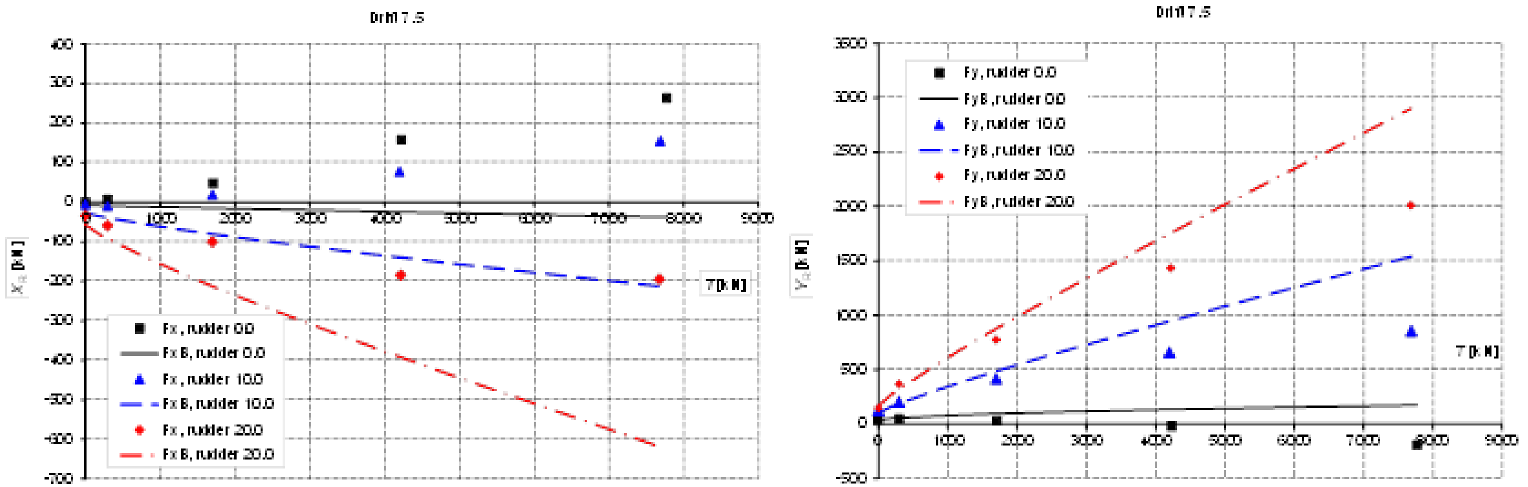
Simplification 4 of Söding Model (Brix, 1993) (3)



original model



simplified model

=> non conservative

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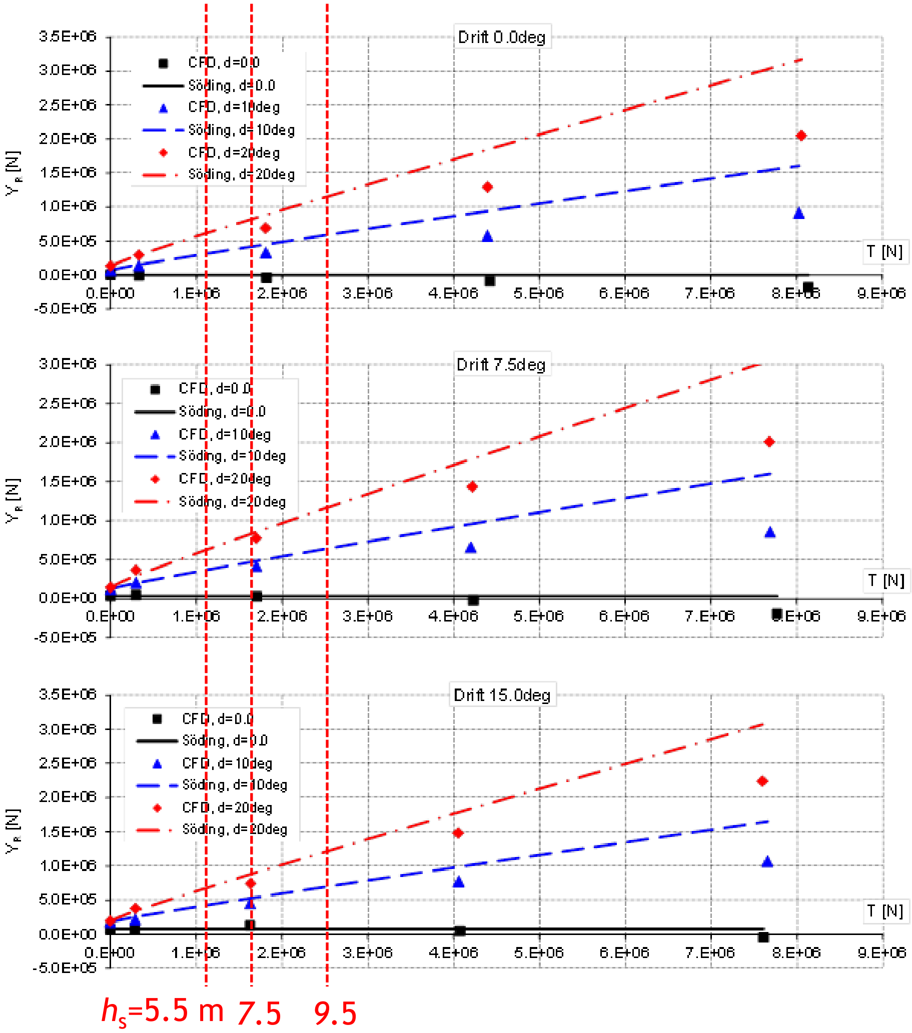
Söding Model (ONR, 1998)

- H. Söding, Limits of potential theory in rudder flow predictions, ONR Symp. On Naval Hydrodynamics, 1998, and Ship Technology Research – Schiffstechnik, 1998, Nr. 4, 141-155
- Additional lift on the rudder due to working propeller:

$$\Delta L = T\left(1+1\Big/\sqrt{1+C_{th}}\right)\sin\delta_R$$

δ_R is rudder angle

- Similarly simple formula for longitudinal force on rudder X_R
- Very well suitable for Level 1
- Lateral force Y_R ok at small propeller loading, <u>non-conservative at high loading</u>



Rudder Models: Summary

- Söding Model (Brix, 1993):
  - perhaps rather Level 2 model – seems too complex for Level 1
  - Agreement of lateral force is very good
  - Simplifications make the model worse => keep it as it is
  - Thrust on rudder can be accounted for, if not – not critical: conservative, otherwise Level 3 data
- Söding Model (ONR, 1998):
  - Very well suitable for Level 1
  - Lateral force Y_R is predicted well at small propeller loading
  - At high propeller loading, Y_R is over-predicted: corrections may be required

Contact

Vladimir Shigunov
vladimir.shigunov@dnvgl.com
+49(0)40361495624

www.dnvgl.com

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