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Approximate Method of Calculating Forces on Rudder During Ship Sailing on a Shipping Route

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ABSTRACT: Service speed of a ship in real weather conditions is a basic design parameter. Forecasting of this speed at preliminary design stage is made difficult by the lack of simple but at the same accurate models of forces acting upon a ship sailing on a preset shipping route. The article presents a model for calculating forces and moment on plane rudder, useful for forecasting of ship service speed at preliminary stages of ship design.

1 INTRODUCTION

When a transport ship is sailing on a given sailing route in real weather conditions, a number of factors – plane rudder action, among others – influence actual service speed of a ship. When a ship is acted upon by wind and wave of oblique directions, this results in additional resistance, drift force and ship rotating moment (in order to maintain a preset ship course this moment has to be counterbalanced by the moment of deflected rudder blade). When plane rudder is deflected, apart from additional resistance, a side force emerges on a rudder causing the ship to drift. Various methods for calculating the forces and moment on plane rudder located behind a propeller are known from literature [1], [2]. Such methods are useful for examining ship maneuverability properties. They are not good, however, to forecast ship service speed in real weather conditions at preliminary ship design. At this stage, ship hull shape, propeller characteristics and propelling engine parameters are not yet known. Therefore forecasting ship's service speed, models based only on basic geometrical parameters of a designed ship are highly useful, among other to calculate additional resistance from deflected plane rudder.

The article presents an approximate method of calculating forces on plane rudder located behind a propeller, useful for forecasting service speed of a ship at initial stage of its design.

2 FORCES AND MOMENT ON A RUDDER LOCATED BEHIND A PROPELLER

When a ship is sailing on wavy water, in particular when the ship is acted upon by wind and wave from oblique directions, side forces and moments emerge which enforce changes on sailing route and result in a drift. In order to maintain constant course, rudder has to be deflected (Fig. 1) which causes additional resistance X_R.

In literature on ship maneuvering, there are numerous algorithms to calculate hydrodynamic forces on rudder, e.g. [3], [4], including also additional resistance [5]. According to [4] forces on a rudder can be calculated from the equations below:

$$X_R = \left| F_N \sin \delta_R \right|,$$
$$Y_R = a_y F_N \cos \delta_R, \quad (1)$$
$$M_R = a_z F_N \cos \delta_R,$$

where:

δ_R – rudder angle (Fig. 1 – rudder angle at port side →$\delta_R > 0$, rudder angle at starboard →$\delta_R < 0$),
a_y – influence coefficient of the hull over Y_R force on rudder,
a_z – influence coefficient of the hull over M_R moment on rudder,

$$a_z = a_y \cdot x_R, \quad (2)$$

x_R – distance of rudder from the ship center of gravity G ($x_R < 0$)
F_N – normal force on rudder,

$$F_N = \frac{1}{2} \rho_w \frac{6.13\lambda}{\lambda + 2.25} A_R V_R^2 \sin \alpha_R, \quad (3)$$

λ – aspect ratio of rudder,
A_R – rudder area,
V_R – velocity of water inflow to rudder,
α_R – effective angle of attack.

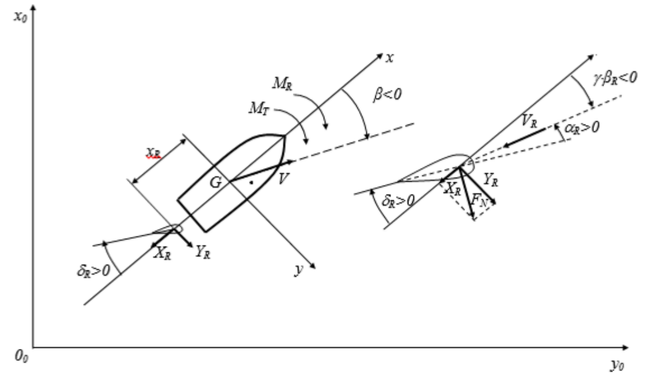


Figure 1. Forces on a rudder

As a result of rudder deflection, a moment M_R from force Y_R emerges – therefore in order to keep the preset course of a ship, the moment on rudder should have such value as to counterbalance the resultant enforcing moment from wind, wave and resistance moment (together with current action) in case of movement with drift angle.

Effective angle of attack of rudder α_R occurring also in equation (3) depends mainly on trajectory of ship movement and direction of inflow to rudder, i.e. drift angle in rudder area.

$$\alpha_R = \delta_R + \gamma \cdot \beta_R, \quad (4)$$

where:

β_R – drift angle at rudder,
γ – coefficient accounting for straightening/correcting action of a ship's propeller and hull (flow straightening coefficient)).

The velocity of water inflow to rudder V_R depends on ship's speed V and the wake and slipstream behind a propeller:

$$V_R = V(1 - w_R)\sqrt{1 + K_2 \cdot G_S}, \quad (5)$$

where:

w_R – wake fraction in rudder area,
K_2 – influence coefficient of propeller over rudder,
G_S – load coefficient of a propeller.

Taking into account prior assumptions to the presented algorithm according [4] i.e. that the ship sails with constant speed and its rudder is deflected only inasmuch as to counterbalance external moments to maintain the preset course of a ship, then:

$$w_R \cong w_T, \quad (6)$$

$$G_S = \frac{D_p}{b_R} \cdot \frac{0.6(2 - 1.4s)s}{(1 - s)^2}, \quad (7)$$

D_p – propeller diameter,
b_R – rudder height,
s – slip ratio of propeller,

$$s = 1 - \frac{V(1 - w_T)}{P \cdot n_p}, \quad (8)$$

w_T – wake fraction,
P – propeller pitch,
n_p – propeller revolutions.

3 APPROXIMATION OF FORCES AND MOMENT ON PLANE RUDDER

The above algorithm for calculating forces on plane rudder contains a number of parameters regarding ship hull, rudder as well as a propeller and engine which are not known at initial stage of ship design.

In order to work out a simple approximating formula, the following assumptions have been made:

- From carried out calculations of the drift angle value β_R in rudder area [6] and distribution of this angle performed during ship movement along a shipping route (examples of obtained results – Fig.2), it has been assumed that effective rudder angle (4) equals:

$$\alpha_R \cong \delta_R, \quad (9)$$

- Rudder area A_R and aspect ratio λ will be made dependant on basic ship dimensions.

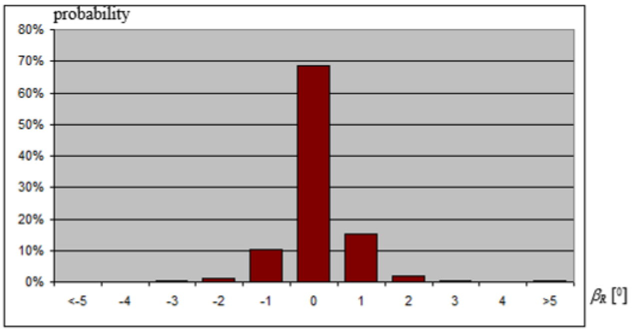


Figure 2. Histogram of drift angle for containership K1 on a shipping route between Western Europe – East Coast of USA (mean drift angle β_R = 0.075)

Search for relationship between A_R from ship dimensions has been performed for:

- various ship types (129 ships altogether),
- for specific ship types, eg. container ships, bulk carriers, tankers.

During our research, it has turned out that the division into specific ship types does not give us a significant increase of approximation adjustment to model values.

Exemplary results of obtained approximations of rudder area have been given in Fig. 3-6.

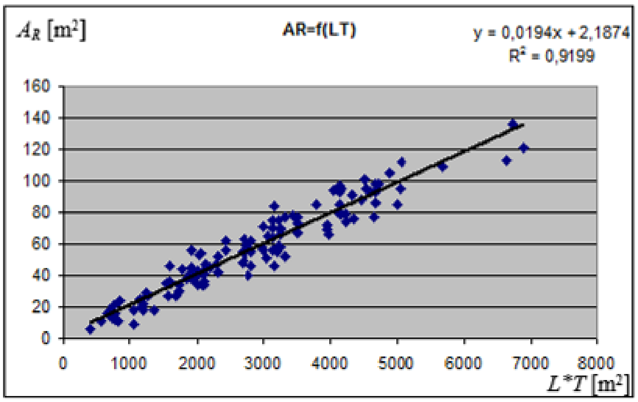


Figure 3. Approximation of rudder area A_R depending on a product of the ship length between perpendiculars L and draught T for various ship types (129 ships altogether)

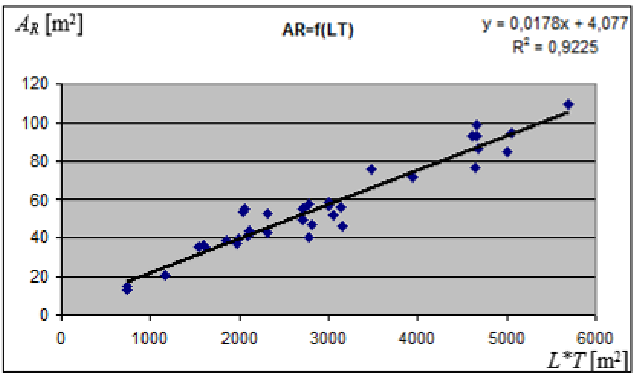


Figure 4. Approximation of rudder area AR depending on a product of the ship length between perpendiculars L and draught T for bulk carriers (37 ships)

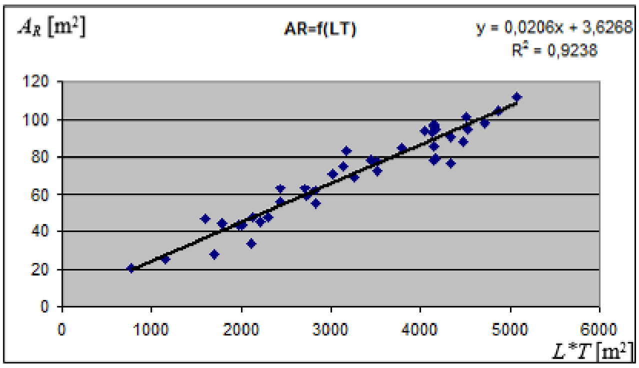


Figure 5. Approximation of rudder area A_R depending on a product of the ship length between perpendiculars L and draught T for container ships (42 ships)

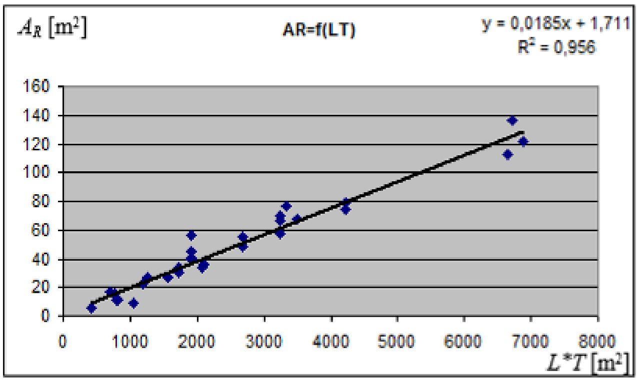


Figure 6.Approximation of rudder area A_R depending on a product of the ship length between perpendiculars L and draught T for tankers (31 ships)

Based on carried out calculations, it has turned out that rudder aspect ratio λ depends on ship dimensions only in a very small degree, therefore for specified ship types constant mean values can be adopted:

- bulk carriers $\lambda = 1.695$,
- container ships $\lambda = 1.795$,
- tanker $\lambda = 1.826$.

Functions approximating forces and moment on rudder have been searched for in the form:

$$\left.\begin{matrix} X_R \\ Y_R \\ M_R \end{matrix}\right\} = f(V, \delta_R, \text{basic ship dimensions}) \qquad (10)$$

with the assumption that, rudder angle δ_R will only change within a small range on a given shipping route – example of calculation (to algorithm [7]) results for rudder angle distribution for a containership on a given shipping route have been presented in Fig. 7.

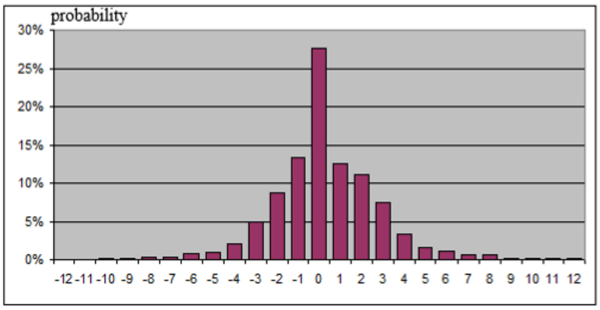


Figure 7. Histogram of rudder angle for a containership K1 on a sailing route between Western Europe and East Coast of USA. (mean rudder angle $\delta_R = 1.40$)

Apart from ship geometric parameters and rudder angle, ship speed V occurs in equation (3) – normal force on rudder as well as in equation (8) – slip ratio of propeller. It has therefore been assumed, that approximating model for rudder inflow velocity will take the form of:

$$V_R = a + b \cdot V \tag{11}$$

Taking into account approximation of rudder area A_R and aspect ratio λ the final expressions of forces and moment on rudder are the following:

$$\begin{gathered} X_R = \left|(0.0194 \cdot L \cdot T + 2.1874) \cdot c \cdot (a + b \cdot V)^2 \sin^2 \delta_R\right|, \\ Y_R = \frac{1}{2}(1.14 - 0.6 \cdot C_B) \cdot (0.0194 \cdot L \cdot T + 2.1874) \cdot c \cdot (a + b \cdot V)^2 \sin 2\delta_R, \\ M_R = -\frac{1}{4} L_{PP}(1.14 - 0.6 \cdot C_B) \cdot (0.0194 \cdot L \cdot T + 2.1874) \cdot c \cdot (a + b \cdot V)^2 \sin 2\delta_R, \end{gathered} \tag{12}$$

where: $c = \left(\frac{1}{2}\rho_w \frac{6.13\lambda}{\lambda + 2.25}\right)$.

Table 1. Coefficient values a, b, c for an adopted model of various ship types

	a [m/s]	b [-]	c [kg/m³]
bulk carriers	4.252	0.262	1.3498
container ships	5.333	0.329	1.3941

4 VERIFICATION OF WORKED OUT APPROXIMATIONS AND FINAL CONCLUSIONS

Comparison of calculations performed according to algorithm described in section 2 [7] with the results obtained from approximating formulas (12) for selected ships, whose basic parameters are given in Table 2, has been presented in Fig. 8÷11.

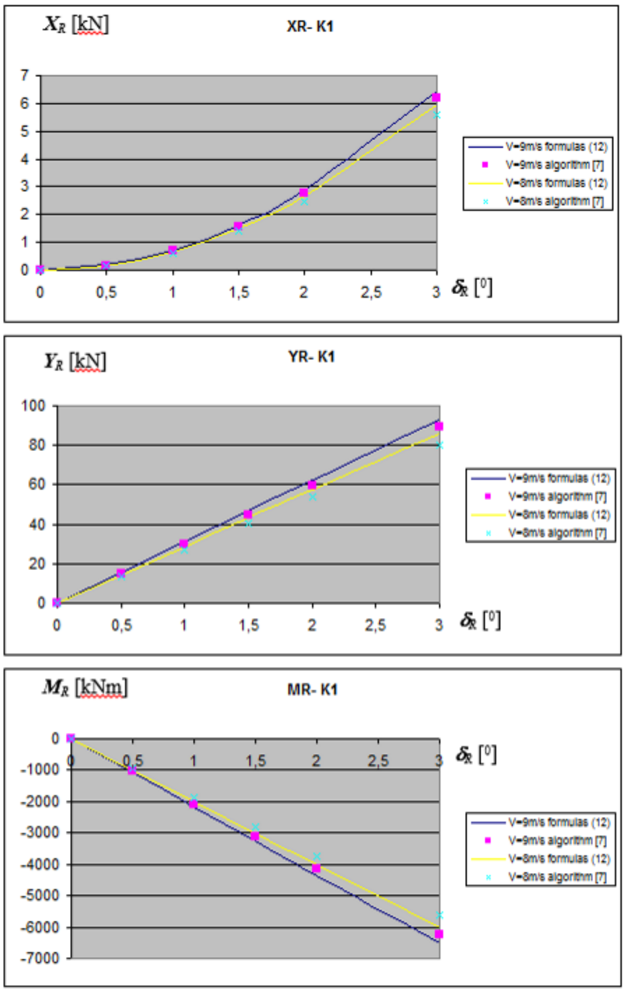
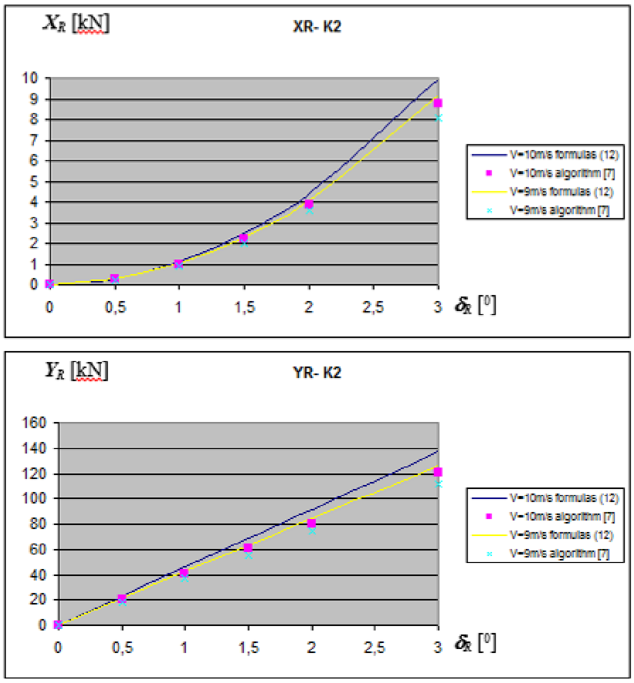


Figure 8. Forces and moment on rudder calculated for obtained approximations (12) and according to the algorithm [7] for a container ship K1 and two values of ship



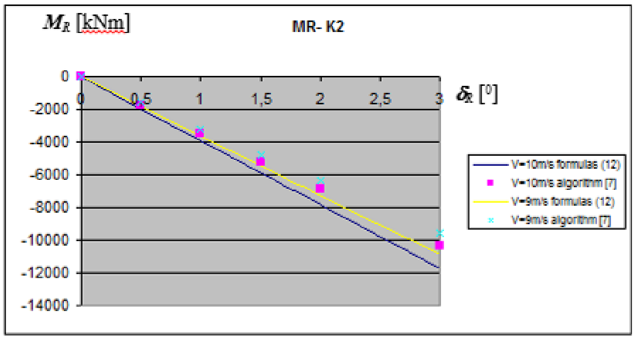


Figure 9.Forces and moment on rudder calculated for obtained approximations (12) and according to the algorithm [7] for a container ship K 2 and two values of ship speed

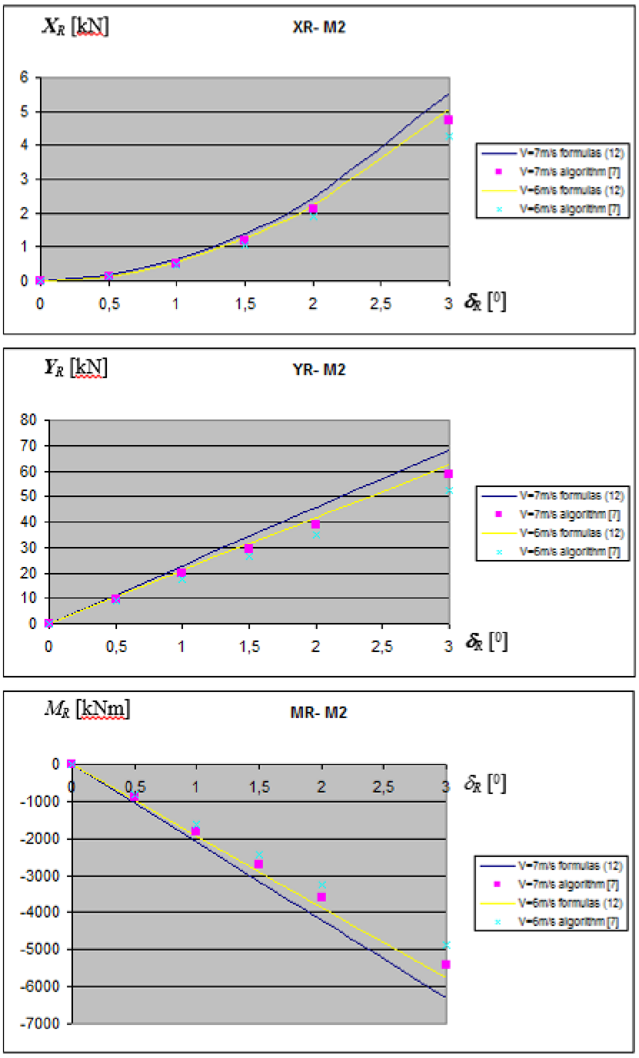


Figure 10. Forces and moment on rudder calculated for obtained approximations (12) and according to the algorithm [7] for a bulk carrier M 2 and two values of ship speed

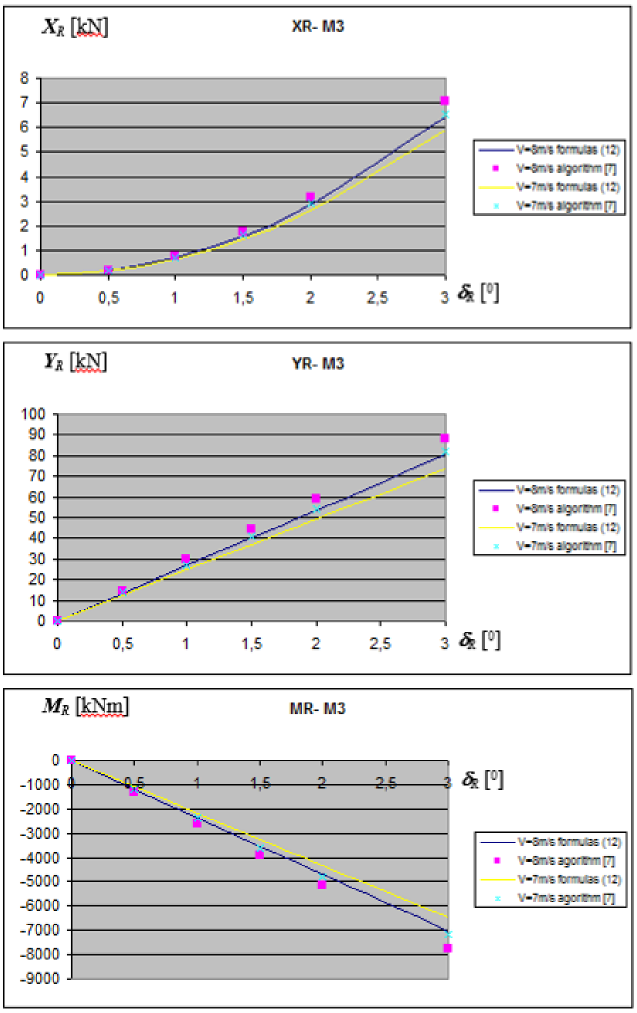


Figure 11. Forces and moment on rudder calculated for obtained approximations (12) and according to the algorithm [7] for a bulk carrier M3 and two values of ship speed

Table 2. Basic exemplary ship parameters used for model verification

	K1 container ship	K2 container ship	M2 bulk carrier	M3 bulk carr.
ship length between perpendiculars L_{PP} [m]	140.14	171.94	189.9	180.0
ship breadth B [m]	22.3	25.3	25.3	32.2
draught T [m]	8.25	9.85	10.6	12.0
block coefficient C_B	0.641	0.698	0.820	0.805
waterplane area coefficient C_{WP} [-]	0.809	0.828	0.854	0.873
displacement volume V [m^3]	17290	29900	40831	56396
ship speed V [m/s]	9.31	10.08	7.51	8.69

Results presented in Fig. 8÷11 have been calculated for small rudder angles δ_R, since in order to keep a ship on a given shipping route, the rudder will only be deflected to a small degree in most cases, Fig. 7 [7]. For such small rudder angles, approximations presented here are accurate enough. Approximations worked out here are highly useful to test, already at initial stage of ship design, service speed of the ship in real weather conditions on a preset shipping route.

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