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# Calculation of influence of propeller slipstream on marine rudder performance

SUMMARY

*An advanced computational method was applied to calculate forces and moments developed on marine rudder located in propeller slipstream. The common vortex lattice model was applied for screw propeller to determine velocity distribution in propeller slipstream. Surface vorticity distribution was used to calculate pressure distribution on rudder surface.*

*A series of calculations was performed to validate the method and the prepared computer program. Obtained results, compared with the available experimental data, confirmed the reliability of the presented model.*

## INTRODUCTION

Marine rudders are the most common passive steering devices. They are usually located in propeller slipstream. Such location on one hand enhances their performance but on the other tightly relates the characteristics of a rudder to the operating parameters of propeller.

In the usual course of design the side force and moment developed on a rudder are evaluated by using characteristics of infinite span airfoils in uniform stream. The actual span of a rudder is accounted for by application of the Prandtl formulae. The effect of screw propeller operation is taken into account in the calculations by including the mean axial velocity of propeller slipstream. This velocity is a function of propeller loading and is usually evaluated according to the actuator disk theory. Additional correction factors are applied to account for an actual outline (or planform) of a rudder. The factors are derived from experimental data and do not cover the whole range of possible rudder outlines.

All above mentioned approximations and corrections contribute to errors, the magnitude of which is hard to estimate. The forces and moments applied to strength calculations and steering gear design are usually multiplied by a factor of safety and therefore become highly overestimated.

The authors proposed a theoretical model of flow in a system comprising marine rudder and screw propeller in order to reduce the uncertainty in evaluation of side force and moment acting on a marine rudder. It is aimed at calculating the performance of an arbitrary rudder located in propeller slipstream. The model accounts for the actual geometry of a rudder (including its outline and thickness distribution) as well as spatial variation of inflow velocity. The velocity in ambient flow results from superposition of inflow velocity and that induced by operating propeller. The calculations can be performed for full range of propeller loading. The rudder can be shifted transversely as well as in the axial direction relative to propeller disk. The assumed potential flow about a rudder does not cover effects of viscosity. This problem is hoped to be solved in the further development of the model.

## MODEL OF FLOW AROUND A RUDDER

The surface vorticity was applied to solve the flow about a rudder in a nonuniform stream. Also utilised was an ample experience acquired before from modelling a partial nozzle of ducted propeller [1] and of so-called wake equalizing ducts (WED) attached to a hull in the front of propeller [2]. The details of application of the method can be found in the quoted references therefore a brief description only is included below.

The surface of a rudder is replaced with an infinitesimally thin vortex sheet. The Dirichlet-type boundary condition (zero tangent velocity on the inner surface of vortex sheet), written for an arbitrary point of the vortex sheet (except sharp edges), takes a form of two coupled Fredholm integral equations of second kind. A set of linear algebraic equations is obtained after discretization necessary to solve the equations numerically. The RHS vector contains tangent components of velocity in „undisturbed" flow at the control points selected on rudder surface during discretization. The undisturbed flow velocity is a sum of the inflow velocity in absence of propeller and rudder and the velocity induced by operating screw propeller. At the tips of a rudder, the loading and hence bound vorticity is reduced to zero which implies strong trailing vortices extending along the tip edges and farther from trailing edge to infinity. Test calculations revealed that this model, especially when applied to thick airfoils, results in an inadequate spanwise load distribution in the vicinity of tips. This is because of poor approximation of viscous effects in the tip region. A smooth interpolation was applied to spanwise distribution of loading in a small region adjacent to tip edges of a rudder in order to cure the problem and avoid increasing complexity of the model.

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The wake extending downstream a rudder is approximated with an array of vortex lines attached to trailing edge.

The strength of surface vorticity is determined by solving the set of linear algebraic equations that represent boundary condition written for each control point on the surface of a rudder. As the strength of vorticity at any point of the ruder surface is equal to the value of tangent velocity at this point, the pressure distribution on a rudder can be calculated straightforward by application of Bernoulli equation. Forces and moments developed on a rudder blade are then calculated by integration of the pressure.

The rectangular integration in the chordwise direction (on airfoil section), corresponding to constant strength of vorticity on each panel, and trapezoidal integration in the spanwise direction was applied. The centre of pressure or a point where lift force is applied can be calculated as usual by dividing a moment by an appropriate force.

Some test calculations have been performed in order to validate the presented model. Results obtained for the rectangular rudders of aspect ratio $\lambda$=1.0 and $\lambda$=1.5 are compared with the experimental data presented in [3]. The rudders had NACA 0009 and NACA 0024 airfoil sections. In the range of linear relation between lift and angle of attack satisfactory agreement of the theoretical and experimental results was obtained.

Additional test calculations have been performed for a trapezoidal rudder.The obtained results compared with the experimental data [4] are presented in Fig.1. Slightly overestimated values of lift coefficient result from neglecting viscous effects.

The described model can be applied to analyse the flow around a rudder in nonuniform velocity field, with no additional modifications.

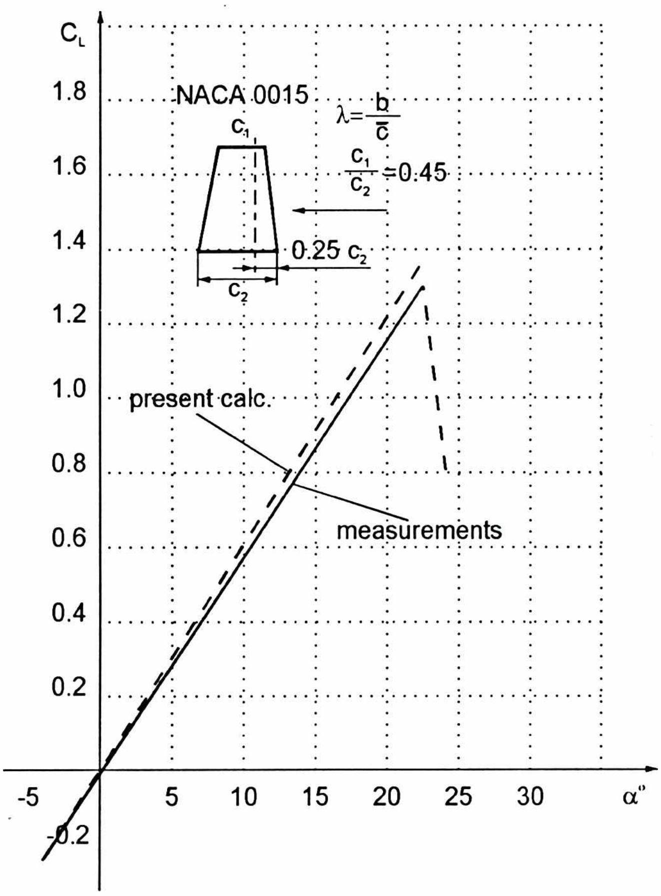

*Fig. 1. Hydrodynamic characteristics of trapezoidal rudder*

## INTERACTION OF PROPELLER SLIPSTREAM AND MARINE RUDDER

The common vortex lattice model of screw propeller [5] was employed to evaluate velocities in propeller slipstream. The general Cartesian reference system is shown in Fig.2 x-axis coincides with the propeller axis and the origin is located in the centre of propeller disk.

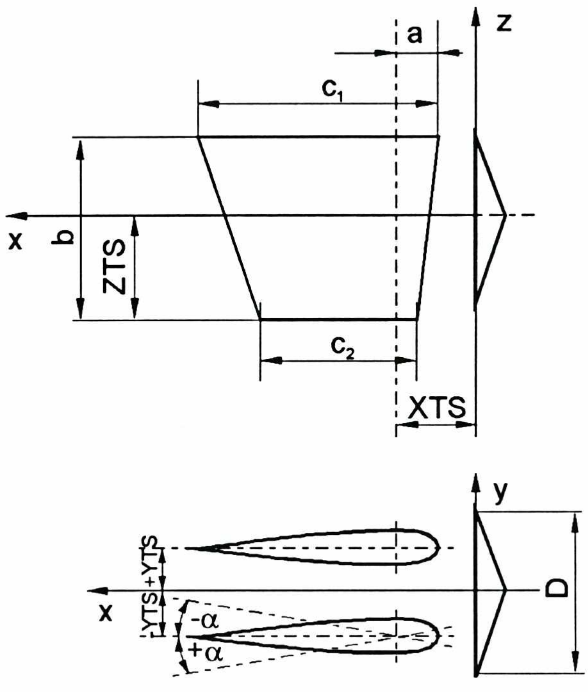

*Fig.2. Coordinate system applied in calculations*

The system of screw propeller and rudder is immersed in a uniform stream of velocity $v_A$. The „ undisturbed " velocity in the control points on the rudder surface is a sum of the inflow velocity $v_A$ and a velocity induced at a given point by the entire vortex system, modelling propeller blades (bound and trailing vortices distributed on the mean surfaces of propeller blades) and wake (helical free vortices extending from trailing edge of each blade to infinity downstream the propeller). If any free vortex is about to cross the surface of a rudder its geometry is modified in such a way that starting from the point of „ collision „ the vortex is aligned with the rudder surface. If the free vortex passes close to a control point on the rudder surface, some correction is introduced in order to avoid excessive values of induced velocities [5].

A velocity induced by screw propeller is calculated in turn at each control point on rudder surface. Next the mean value of it is computed for each chordwise array of the control points, separately for the suction and pressure side of a rudder. In this way the spatial variation of the induced velocity is smoothed out due to the discrete model of propeller wake.

In order to confirm the reliability of the model a series of tests and calculations of side force developed on various rudders in propeller slipstream were performed. Three following rudders were considered : two rectangular rudders of NACA 0024 airfoil section and aspect ratios of 1.0 and 1.5 [6], and one trapezoidal rudder of NACA 0018 airfoil section [7]. The geometry of a system and the operating conditions used in the calculations were the same as in the experiments. The results have been compared with available experimental data.

A propeller applied in the case of rectangular rudders was the four-bladed screw propeller of the pitch-diameter ratio P/D=1.04 and the blade area ratio $A_E/A_O$=0.565.

Its rotational speed was kept constant at n=1.67 r.p.s. Its operating parameters in considered operating conditions are collected in the following table:

| $J$ | $v_A$ [m/s] | $c_{Th}$ | $v_{AN}$ [m/s] |
|---|---|---|---|
| 0.1 | 0.245 | 107.0 | 2.335 |
| 0.3 | 0.734 | 10.0 | 2.271 |
| 0.5 | 1.223 | 2.8 | 2.269 |

where:

$J$ - advance coefficient
$v_A$ - velocity in uniform stream
$c_{Th}$ - coefficient of thrust propeller loading
$v_{AN}$ - mean velocity in propeller slipstream at rudder's leading edge (taken as a reference value used for calculation of lift coefficient).

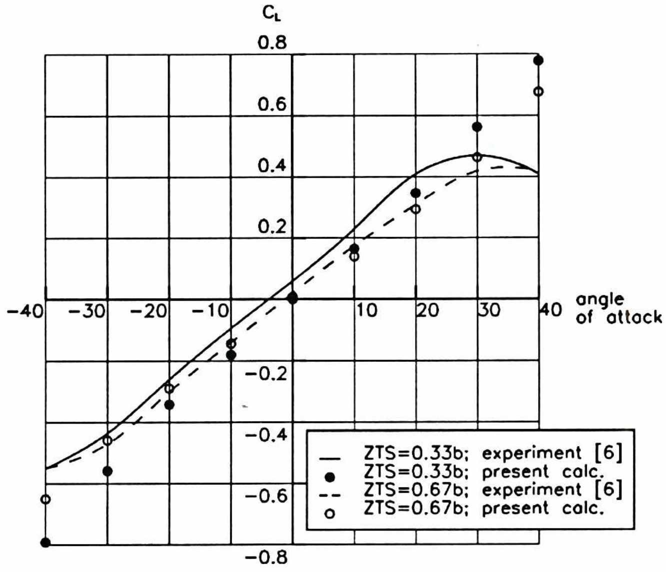

*Fig.3. Effect of vertical shift of rectangular rudder on its hydrodynamic characteristics $\lambda=1.5$ $J=0.1$*

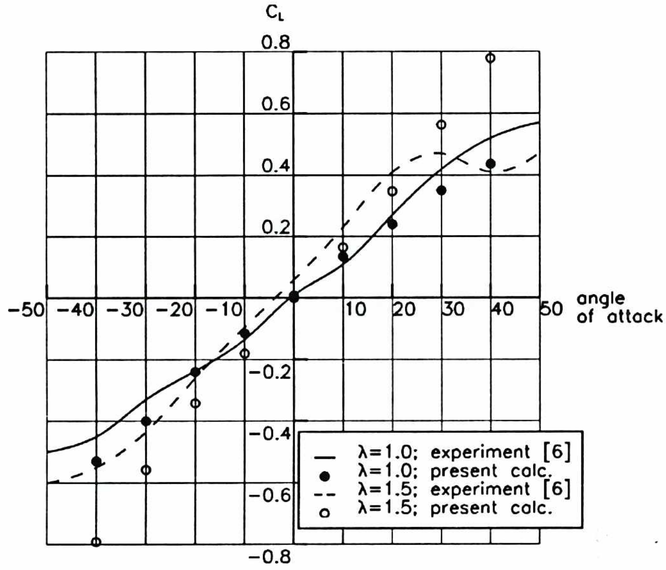

*Fig.4. Effect of aspect ratio on hydrodynamic characteristics of rectangular rudder $J=0.1$ $ZTS=0.33b$*

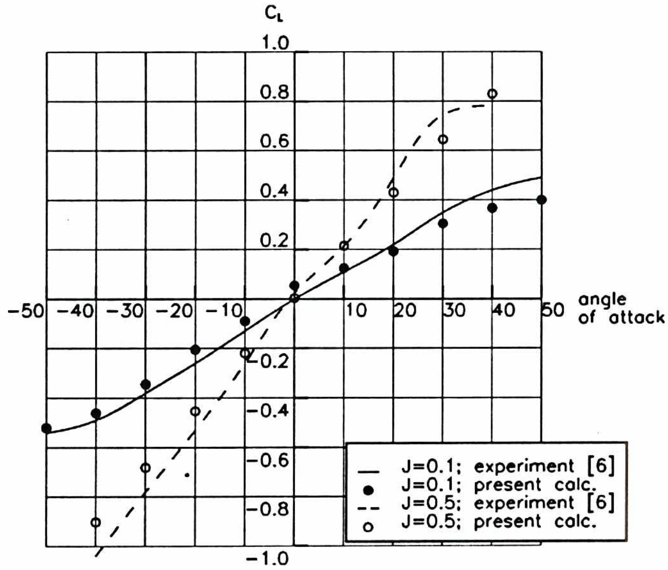

*Fig.5. Effect of propeller loading on hydrodynamic characteristics of rectangular rudder $\lambda=1.0$ $ZTS=0.67b$*

Both rudders had the same span of 0.21 m. Each time the rudder post was arranged in x-y plane central in relation to propeller disk (YTS=0, see denotations in Fig. 2) and three rudder vertical positions were considered. Sample results of the calculations are presented in Fig. 3 to 5 and compared with the experimental data [6]. As it is shown in Fig.3 the vertical position of a rudder has no essential effect on the rudder characteristics. Even a large value of the vertical shift results in a small increment of characteristics's slope. If a rudder is shifted from the vertically central position (ZTS= 0.5b) the magnitude of lift force is not symmetrical in relation to zero angle of attack.

The effect of span is identical as that in the case of uniform flow (see Fig.4) and is apparent especially in the results of calculations.

The screw propeller loading has even more pronounced influence on rudder's characteristics. It can be observed from both experimental and theoretical results shown in Fig.5. One should keep in mind, however, that lift coefficient is reffered to the mean velocity in propeller slipstream $v_{AN}$.

In the case of the trapezoidal rudder two B4-55 screw propellers of the common B-Wageningen series, of the pitch-diameter ratio P/D=0.6 and P/D=1.0 respectively, were applied. Both had the diameter D=0.18 m. Geometry of the trapezoidal rudder was defined by the aspect ratio $\lambda=1.75$, span b=0.225 m and the upper to lower edge chord ratio of 1.61. The tests [7] and calculations in question were performed at two axial (along x- axis: XTS=0.97 m; XTS=0.124 m) and three horizontal (in x-y plane) positions of the rudder (YTS=0; YTS=±0.036 m). The vertical ( in x-z plane) position of the rudder was defined by ZTS=-0.088 m. Sample results for the rudder are presented in Fig. 6 to 8.

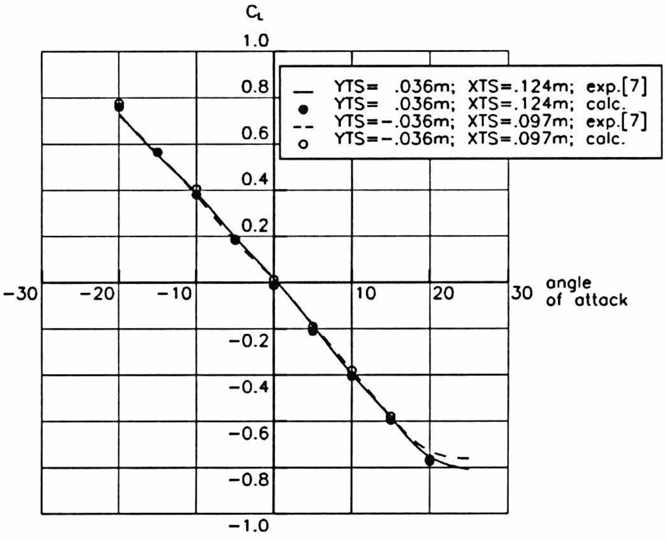

*Fig.6. Effect of horizontal ( in x-y plane) and axial (along x-axis) shift of trapezoidal rudder on its hydrodynamic characteristics; $P/D=1.0$; $c_{Th}=0.47$*

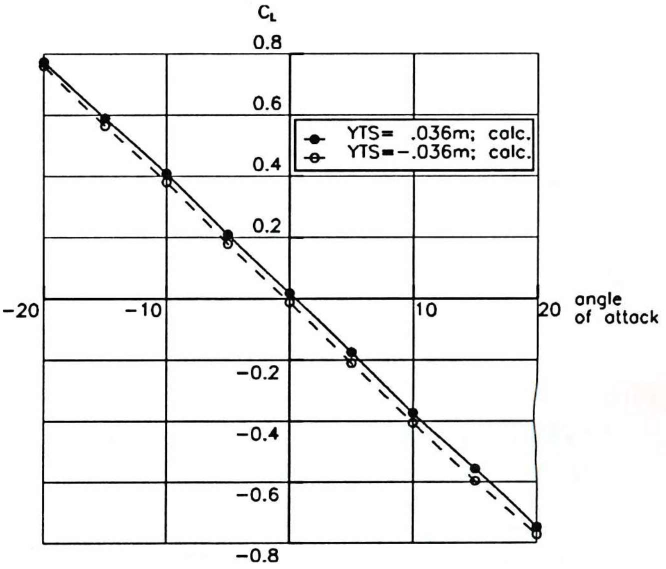

*Fig.7. Effect of horizontal shift of trapezoidal rudder on its hydrodynamic characteristics $P/D=1.0$ $c_{Th}=0.47$*

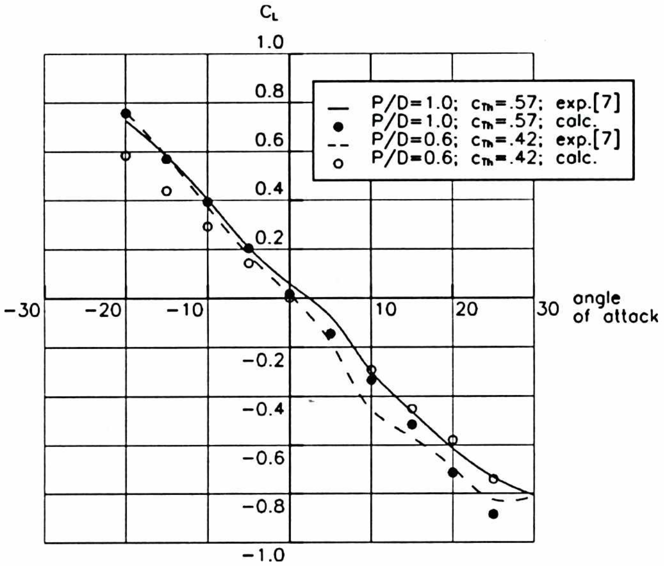

*Fig.8. Effect of propeller pitch-diameter ratio on hydrodynamic characteristics of trapezoidal rudder*

The experimental data as well as the results of calculations reveal only a small effect of rudder position on its performance (see Fig.6). Even the direction of rudder inclination (to starboard or port side) effects slightly the magnitude of developed side force.

In Fig.7 the calculation results only are shown for two extreme horizontal positions of a rudder (YTS=+0.036 m and YTS=-0.036 m). For the intermediate position (YTS=0) the lift curve lies between the characteristics presented in Fig.7.

The effect of propeller blade pitch on rudder characteristics is illustrated in Fig.8. The comparison is only of a qualitative character because propeller loading coefficients, although small, differ by 35 %. In general, rudder's lift coefficient is greater in slipstream of propeller of a higher pitch.

## CONCLUDING REMARKS

In opinion of the authors the presented results confirm that the proposed model can be reliably applied to evaluate rudder performance in propeller slipstream. Although the influence of a rudder on propeller flow has not been taken into account in the performed calculations, the model is flexible enough to include this interaction. However, these results and also the authors' experience in application of the surface vorticity method indicate that this influence can be neglected without detriment to accuracy.

The prepared computer routines can be applied to determine the hydrodynamic characteristics of a marine rudder located downstream the propeller, arbitrarily positioned in relation to the propeller axis. The applied vortex lattice model of screw propeller allows to consider screw propellers of an arbitrary geometry, at any given forward operating conditions.

In order to extend the applicability of the model, it is going to be developed to include effects of water viscosity. Application of the viscous-inviscid interaction method would allow to calculate rudder resistance and account for limited trailing edge separation of boundary layer.

### *Acknowledgement*

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***Appraised by Tadeusz Koronowicz, Assist.Prof.,D.Sc.,N.A.***

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# Current reports

POLISH ACADEMY OF SCIENCES
INSTITUTE OF FLUID FLOW MACHINERY
GDAŃSK

## A new method for analytical prediction of hydroacoustic pressure generated by ships

In the second quarter of 1995 a new research grant was initiated in the Institute of Fluid Flow Machinery in Gdańsk, entitled: „Analytical Determination of the Acoustic Pressure Field Resulting from Ship Flow and Propeller Operation". The project leader is Tadeusz Koronowicz, Assist.Prof.. The purpose of the project is development of the computer system for prediction of the acoustic pressure field induced by the moving ship with operating propeller. This program will be an important tool for design of geophysical and fishing vessels, but first of all for naval ships. The program will enable optimization of the hull-propeller configuration at different stages of design. It will also facilitate the analysis of full scale acoustic measurements.

Algorithm of the program is based on the following theoretical models:

- velocity and primary pressure field around the hull is determined using boundary element method with sources distributed on quadrilateral panels representing the hull
- secondary pressure field due to wave system of the water surface is based on the Green function being the solution of Laplace equation for a moving pressure impulse
- turbulent boundary layer on the hull is modelled using integral boundary layer equation solved along the streamline
- acoustic pressure field generated by the propeller is modelled by unsteady lifting surface and double layer lifting surface theory, which include cavitation effects.

A series of full scale and model experiments forms an integral part of the research project. These experiments will provide data necessary for validation of the computer programs. The project is carried out in cooperation with specialists from the Naval Academy in Gdynia. Up to now the computer programs calculating acoustic pressure field produced by the moving hull have been developed and tested. Initial results of calculations have been confronted with published data and have been assessed by hydracoustics specialists. According to their opinion results of unique quality have been obtained. The project will be completed in the middle of 1997.