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CFD Based Hull Hydrodynamic Forces for Simulation of Ship Manoeuvres

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ABSTRACT: There have been developed numerous mathematical models describing the motion of a ship. In opinion of present authors the CFD is mature enough to determine with confidence the hydrodynamic characteristics necessary to simulate ship manoeuvres. In this paper the authors present the attempt to determine the hull hydrodynamic forces using the results of CFD computations of ship flow. Results show qualitative agreement with reference data and reveal shortcomings due to simplifying assumptions applied in CFD computations.

1 INTRODUCTION

During the process of designing a new ship the designer has to answer a lot of questions. Some of them refer to the manoeuvrability of a ship. Moreover, the IMO regulations define precisely the minimum manoeuvring requirements. The possibility to determine the manoeuvring properties in early stage of design results in significant reduction of cost and time. There have been developed numerous mathematical models describing a motion of a ship. The authors of those methods usually report common problems like poor accuracy, limited range of application, or need of model tests to determine characteristics and coefficients. Recent advances in IT and CFD are promising in solving problems referring to the need of model tests. In the opinion of the present authors the CFD is mature enough to determine most of hydrodynamic characteristics necessary to simulate ship manoeuvres. The characteristics of hull, propeller and rudder and interactions between hull, propeller and rudder can be determined separately with confidence. In this paper the authors present the attempt to determine the hull hydrodynamic forces using the results of CFD computations of ship flow.

2 EQUATIONS OF SHIP MOTION

Usually the equations of ship motion are written in the co-ordinate system with the origin at the centre of gravity of a ship. The left-hand sides of equations describe the dynamics of rigid body, and the right hand sides represent the external forces:

$$m\dot{u} - mvr = X$$
$$m\dot{v} + mur = Y$$
$$I_{zz}\dot{r} = N \quad (1)$$

m denotes the mass of a ship, u, v, r - forward speed, transverse speed and yaw rate, $\dot{u}, \dot{v}$ and $\dot{r}$ - accelerations in respective directions, I_{zz} - the moment of inertia of a ship, X, Y and N - the external forces: surge force, sway force and yaw moment, measured at ship's centre of gravity.

The same equations can be written in a co-ordinate system with the origin at midship:

$$m(\dot{u} - vr - x_G r^2) = X$$
$$m(\dot{v} + x_G\dot{r} + ur) = Y$$
$$I_{zz}\dot{r} + mx_G(\dot{v} + ur) = N \quad (2)$$

In this case u, v, r, X, Y, N denote rates and forces measured at midship, and x_G - the distance from the midship to the centre of gravity.

Sometimes it is convenient to solve equations written in co-ordinate system with origin at the centre of gravity when forces are determined at midship:

$$m\dot{u} - mvr = X$$
$$m\dot{v} + mur = Y$$
$$I_{zz}\dot{r} = N - x_G Y \qquad (3)$$

Equations (3) are also used in the following for simulation of ship motion.

3 EXTERNAL FORCES

In order to verify the idea of determination of hydrodynamic forces using CFD the present authors chosen the modular model of MMG to represent the external forces acting on manoeuvring ship:

$$X = X_H + X_P + X_R$$
$$Y = Y_H + Y_R$$
$$N = N_H + N_R \qquad (4)$$

The subscripts "H" "P" and "R" denote the hull hydrodynamic forces and forces from propeller and rudder respectively. This modular model is suitable for testing the individual mathematical models one by one.

3.1 *Hull hydrodynamic forces*

The mathematical model described in [1] was used to represent hull hydrodynamic forces for its simplicity and availability of reference data. Model is based on the quasi-steady approach and forces depend only on rates and accelerations:

$$X'_H = X'_0 + X'_{vv}v'^2 + (X'_{vr} - m'_y)v'r' + X'_{rr}r'^2 + X'_{vvvv}v'^4$$
$$Y'_H = Y'_v v + (Y'_r - m'_x)r + Y'_{vvv}v'^3 + Y'_{vvr}v'^2 r + Y'_{vrr}v'r'^2 + Y'_{rrr}r'^3$$
$$N'_H = N'_v v' + N'_r r' + N'_{vvv}v'^3 + N'_{vvr}v'^2 r' + N'_{vrr}v'r'^2 + N'_{rrr}r'^3$$

u', v', r' denote the non-dimensional rates, X_0 = $-R_T(u)$ - ship resistance in considered co-ordinates, and X'_{vv}, X'_{vr}, ..., Y'_v, Y'_r, ..., N'_v, N'_r, ... - hydrodynamic coefficients.

The non-dimensional forms of forces are defined as follows:

$$X = X' \frac{\rho}{2} L^2 U^2$$
$$Y = Y' \frac{\rho}{2} L^2 U^2$$
$$N = N' \frac{\rho}{2} L^3 U^2$$

3.2 *Propeller force*

The model described in [2] was adopted to represent the longitudinal force generated by propeller, including the effects of propeller-hull interaction:

$$X_P = C_{tP}(1 - t_{p0})n^2 D_P^4 K_T(J_P) \qquad (6)$$
$$K_T(J_P) = C_1 + C_2 \cdot J_P + C_3 \cdot J_P^2$$
$$J_P = U\cos\beta \frac{1 - w_P}{nD_P}$$
$$w_P = w_{P0} \cdot \exp(-4.0\beta'^2)$$
$$\beta' = \beta - x'_P \cdot r'$$

t_{P0} denotes thrust deduction factor in straight ahead ship motion, n - rotational speed of propeller, D_P - propeller diameter, K_T - thrust coefficient, J_P - advance coefficient, C_1, C_2, C_3 - coefficients for evaluation of K_T from open water characteristics, U - ship speed, β - drift angle, w_{P0} - effective wake fraction in straight ahead ship motion, x'_P - non-dimensional x-ordinate of propeller.

3.3 *Rudder forces*

Forces from the rudder, including the interaction between hull, propeller and rudder, are calculated using the mathematical model described in [2] for rectangular spade rudder:

$$X'_R = -(1 - t_R)F'_N \sin\delta$$
$$Y'_R = -(1 + a_H)F'_N \cos\delta$$
$$N'_R = -(x'_R + a_H \cdot x'_H)F'_N \sin\delta \qquad (7)$$

$$\eta = \frac{D_P}{h_R}$$
$$K = 0.6\frac{1 - w_P}{1 - w_R}$$
$$s = 1 - (1 - w_P)U\frac{\cos\beta}{nP}$$
$$w_R = w_{R0}\frac{w_P}{w_{P0}}$$
$$\alpha_R = \delta - \gamma \cdot \beta'_R$$
$$\beta'_R = \beta - 2x'_R \cdot r'$$
$$U_R^2 = (1 - w_R)^2 (1 + C \cdot g(s))$$
$$x'_R = \frac{x_R}{L}$$
$$x'_H = \frac{x_H}{L}$$
$$F'_N = \left(\frac{A_R}{L \cdot d}\right) C_N U_R^2 \sin\alpha_R$$
$$C_N = \frac{6.13 \cdot K_R}{K_R + 2.25}$$
$$g(s) = \eta K \frac{(2 - (2 - K) \cdot s)s}{(1 - s)^2}$$

t_R - denotes the coefficient for additional drag, F_N - normal force acting on rudder, δ - rudder angle (positive to starboard), a_H - ratio of additional lateral force, x'_R - non-dimensional x-ordinate of application point of F_N, x'_H - non-dimensional x-ordinate of application point of additional lateral force, h_R - height of rudder, s - propeller slip coefficient, P - propeller pitch, w_{R0} - effective wake fraction at location of rudder, in straight ahead ship motion, α_R - effective rudder inflow angle, γ - flow straightening coefficient, U_R - effective rudder inflow velocity, A_R - rudder area, K_R - aspect ratio of rudder.

4 HYDRODYNAMIC COEFFICIENTS

The clue of the present paper is the approximation of hull hydrodynamic forces using the results of CFD computations. To this end a series of ship flow computations was carried out for a couple of combinations of drift angle and yaw rate. The scope of drift angle and yaw rate was predetermined based on results of free running model tests of basic manoeuvres, i.e. the turning manoeuvre and the 15/15deg zig-zag manoeuvre [1]. It was estimated that drift angle varies in the range $-10<\beta<20$deg and yaw rate in the range $0<r'<1.0$.

Computations of ship flow were carried out with the assumption of low Froude number (negligible heel and effect of free surface). The commercial Fluent software was used to compute single phase, turbulent steady flow in moving reference frame.

Same assumptions were applied when computing the flow around the accelerating ship, in order to determine the components of added mass: m_x and m_y. In this case the accelerated flow with constant acceleration was computed around ship in rest.

Computed forces, moment and components of added mass were subsequently used to determine all hydrodynamic coefficients in the mathematical model (5). The coefficients were estimated using standard statistics procedure of fitting the user defined function to the set of data.

Reported computations and simulations described in next section were carried out for the *Esso Osaka* model ship of length L_{PP}=6.0m. Hydrodynamic forces approximated using coefficients given in [1] and coefficients based on CFD computations are compared in Fig.1. If one takes the hydrodynamic forces approximated using coefficients from [1] as reference, surge force X'_H seams to be predicted satisfactory. Sway force Y'_H is predicted well except for drift angles above 10deg. Yaw moment N'_H is overpredicted at drift angles above 10deg and at high yaw rate r'>0.4. The effect of differences in hydrodynamic forces on the manoeuvring performance of model ship is shown in the next section.

5 SIMULATION OF STANDARD MANOEUVRES

The turning manoeuvre and the 10/10deg zig-zag manoeuvre of model ship were simulated using equations (3), nodular model (4) of external forces, and mathematical models of hull, propeller and rudder forces described in previous sections. Data for simulation collected from [3] and [4] are listed in table 1. Model ship resistance was estimated according to the idea of form factor:

$$C_{TM} = (1+k)C_{F0M} + C_{RM}$$

There were applied the ITTC-57 model-ship correlation line to evaluate frictional resistance C_{F0M}, the assumption of low Froude number (negligible wave resistance C_{RM}=0), and the form factor k=0.27. Open water propeller characteristics $K_T(J)$ was approximated using the characteristics of corresponding propeller from B-Wageningen screw series.

The differential equations of motion (3) were solved using 4-th order Runge-Kutta method with adaptive time step. However, the examinations shown that this equation can be solved even precisely with simpler methods but with the time step restriction.

Table 1 Data for simulation of motion of the *Esso Osaka* model ship

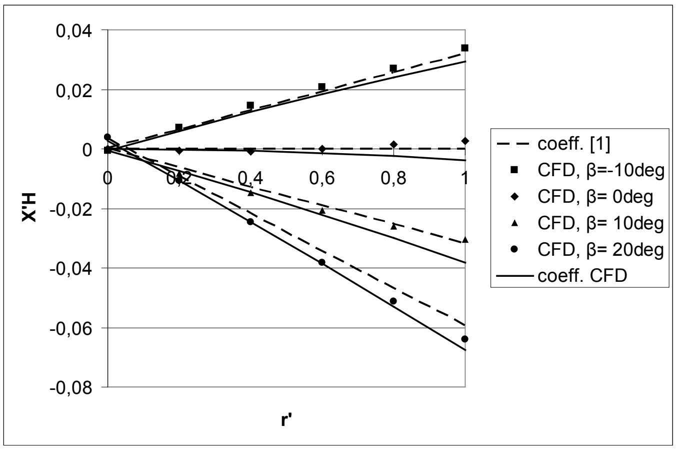
L_{PP}	6.0 m
B	0.978 m
T	0.402 m
C_B	0.83
x_G	0.190 m
$m' = m/\frac{1}{2}\rho L^3$	0.01813
$I'_{zz} = I_{zz}/\frac{1}{2}\rho L^5$	0.00110
$m'_x = m_x/\frac{1}{2}\rho L^3$	0.00138
m'_x (computed)	0.00133
$m'_y = m_y/\frac{1}{2}\rho L^3$	0.01580
m'_y (computed)	0.01703
$J'_{zz} = J_{zz}/\frac{1}{2}\rho L^5$	0.00069
D_P	0.168 m
P/D_P	0.715
t_{P0}	0.27
w_{P0}	0.365
A_R	0.0408 m^2
h_R	0.256 m
K_R	2.49
U_0	0.699 m/s

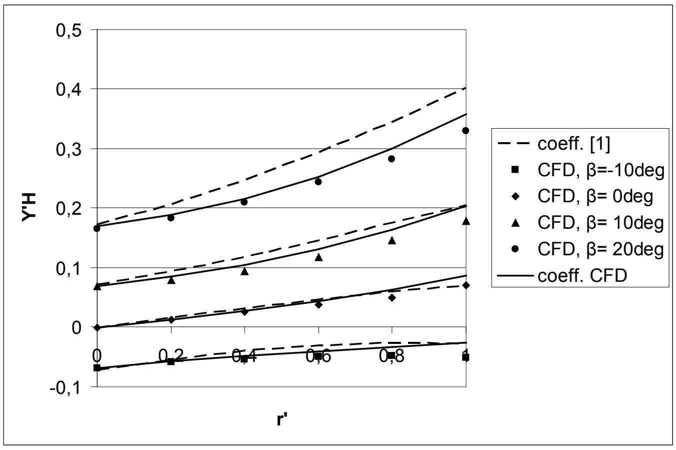
The results of simulation of turning manoeuvre with δ=35deg are shown in figures 2 and the results of 10/10deg zig-zag manoeuvre are shown in figure 3. The differences in estimation of hydrodynamic forces seen in figure 1 are reflected also in results of both simulations.

6 CONCLUSIONS

The authors used the results of CFD computations of ship flow to approximate hydrodynamic forces and moment for simulation of ship manoeuvres. The comparison of hydrodynamic forces approximated using the reference hydrodynamic coefficients and CFD based coefficients, shown in Fig.1, revealed that sway force Y'_H estimated using CFD based coefficients is evidently underestimated at drift angles above 10deg. Yaw moment N'_H is overpredicted at drift angles above 10deg and at high yaw rates $r'>0.4$. That differences in estimation of hydrodynamic forces are reflected also in results of simulations shown in figures 2 and 3.

Taking into account that discrepancies in force estimation and in simulated turning circle appear at higher values of drift angle and yaw rate, one may suspect that the assumption of low Froude number applied to computations of ship flow is valid only at low drift angle and yaw rate. Then at higher values of drift angle and yaw rate the ship heel, trim, sinkage, and especially the effect of free water surface around the ship cannot be neglected in CFD computations.





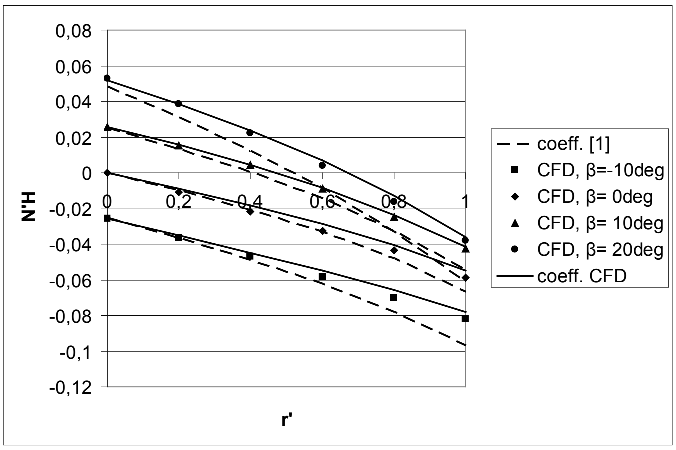
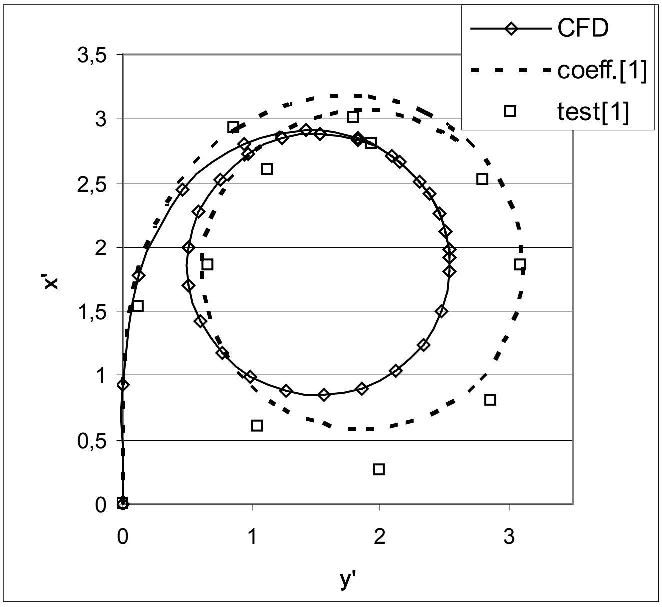
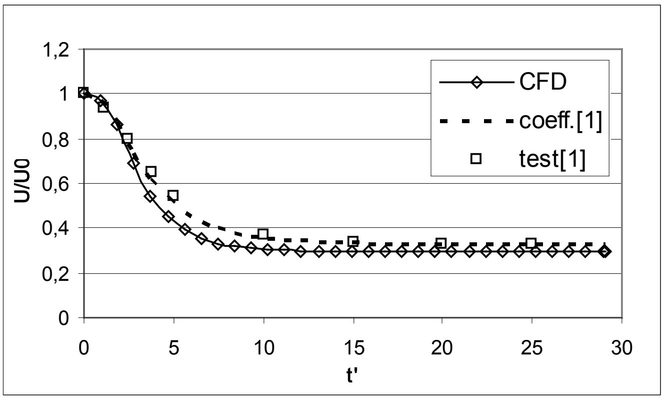


Fig.1. Surge force X'_H, sway force Y'_H, and yaw moment N'_H computed with CFD and approximated using coefficients given in [1] (dashed line) and CFD estimated (solid line).





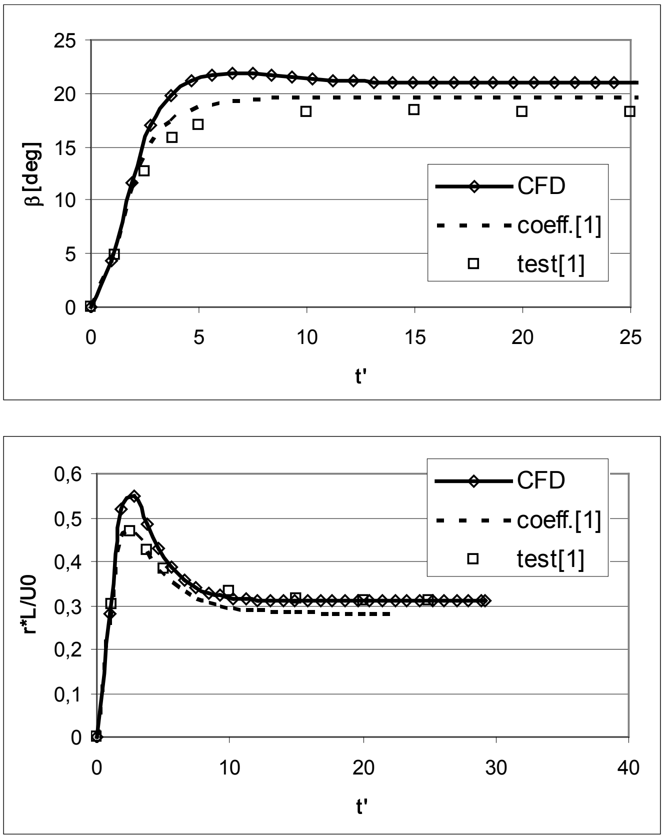
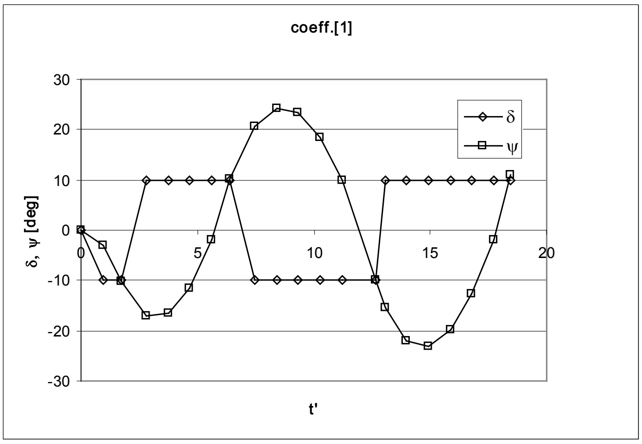


Fig.2. Turning circle of model ship with δ=35deg simulated using hydrodynamic coefficients from [1] and coefficients based on CFD computations

(a)



(b)

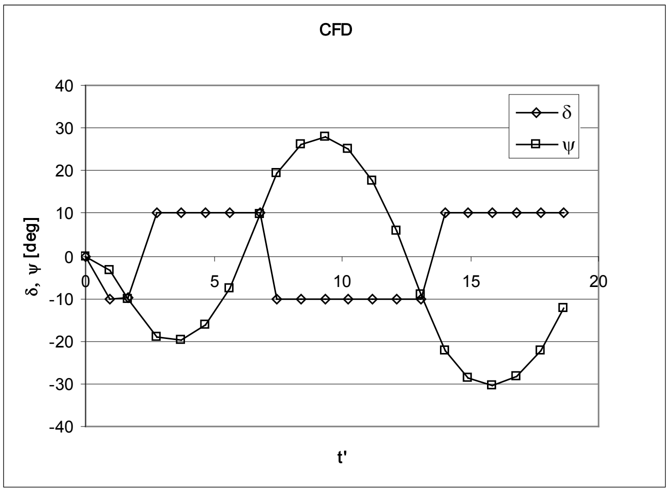


Fig.3. 10/10deg zig-zag manoeuvre of model ship simulated using hydrodynamic coefficients from [1] (a) and coefficients based on CFD computations (b)

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