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# Application of CFD Methods for the Assessment of Ship Manoeuvrability in Shallow Water

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ABSTRACT: Safety in water transport plays a significant role. One way to increase safety in the waterways is to ensure that ships have proper manoeuvrability. Evaluation of manoeuvring properties performed at an early stage of design can detect problems that later would be difficult to solve. To make such an analysis the numerical methods can be used. In the paper the numerical method to evaluate the ship manoeuvrability on the shallow water is presented. Additionally author shows the procedure of determining hydrodynamic coefficients on a basis of CFD calculation. The simulation results of inland ship was compared with experimental data.

## 1 INTRODUCTION

For a long time ship manoeuvring characteristics were considered to be of marginal importance. Nevertheless, from the operational point of view of inland vessels, manoeuvring characteristics play a crucial role. Operating in restricted waterways substantially increases the risk of accidents and disasters as a result of manoeuvring errors. To increase level of safety on the waterways, it is important to ensure that vessels have appropriate manoeuvring characteristics. For this purpose it is necessary to develop research methods for determining the manoeuvring properties of inland ships.

Currently, one of the more commonly used research methods in ship hydrodynamics are numerical methods. With improvements in computing power and increasingly more accurate CFD methods it is possible to simulate more complicated cases. This paper presents a numerical method for prediction of ship manoeuvrability. It is based on a mathematical model of the ship equations of motion, described in section 3. This model requires knowledge of the coefficients of the hydrodynamic forces acting on the ship. In section 4 there is presented a method for determining the hydrodynamic coefficients using CFD.

On inland waters the most restrictive rules are described in Rhine Regulations. The severity of the Rhine Regulations is the result of difficult conditions on the Rhine: a strong current and high traffic intensity. Vessels that fulfil these requirements are allowed to operate on other waterways in Europe. These regulations specify requirements for: a minimum speed of the vessel, the ability to stop, the ability to move backwards and turning manoeuvrability. In addition, there is specified an additional manoeuvre - "evasive action" , which is analogous to zigzag test and is a specific requirement for inland waters. The main characteristic of this evasive action [1] is the moment of switching the rudder to the opposite side, which occurs when the ship reaches the desired angular velocity.

## 2 MATHEMATICAL MODEL OF SHIP MOTION

Motion simulation is based on two coordinate systems. The first one is the global, stationary coordinate system. The ship position and orientation is determined in the global coordinate system. The second one is the local coordinate system. The centre of the local coordinate system is located at the centre of gravity of the ship. Equations of motion of the ship are written in the local coordinate system. Figure 1 shows the two coordinate systems used in the paper. It also shows the velocity components of the vessel.

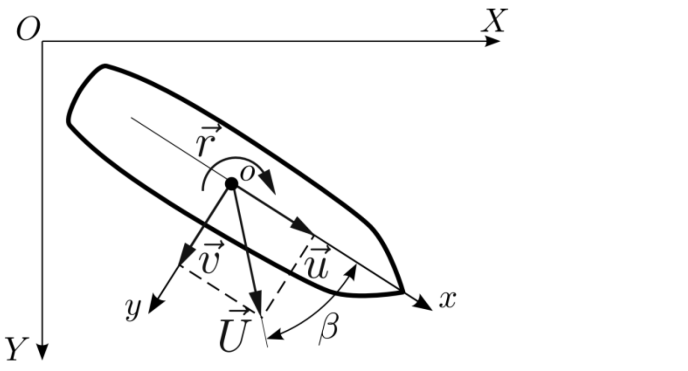


Figure 1. Coordinate systems and velocity components of the vessel.

The movement of the ship is considered to be planar motion (limited to three degrees of freedom).

This study only analysed small velocities at which sinkage and trimming of the ship is minimal. Therefore, these phenomena are not considered in the research..

Interaction between the hull, rudder and propellers are only simulated by appropriate coefficients.

In inland vessels the centre of gravity is far lower than in marine ships. In addition, the centre of gravity is located near the centre of buoyancy. As a result of this , the roll of the vessel is relatively small and could also be neglected.

Wavelength on inland waterways is relatively small in proportion to the length of the vessel. In the study the influence of waves on the trajectory of the ship was not taken into consideration.

The equations of motion (1) were written for the centre of gravity of the ship. The left side of equations describes the ship as a rigid body. On the right side of equations there are hydrodynamic external forces (X, Y) and the hydrodynamic moment (N) acting on the vessel.

$$
\begin{aligned}
& m\dot{u} - mvr = X \\
& m\dot{v} + mur = Y \\
& I_{zz}\dot{r} = N
\end{aligned}
\tag{1}
$$

where:

$m$ – vessel mass; $u$ –longitudinal velocity; $v$ – transversal velocity; $r$ – yaw rate; $\dot{}$ - dot, the derivative of a variable over time; $I_{zz}$ – moment of inertia of the vessel; $X, Y, N$ – hydrodynamic force and moment acting on the vessel according to the axes of local coordinate system. Detailed information about model can be found in [2].

External hydrodynamic forces and the hydrodynamic moment acting on the ship were written like in the MMG model [3], as a sum of the components.

$$
\begin{aligned}
& X = X_H + X_P + X_R \\
& Y = Y_H + Y_R \\
& N = N_H + N_P + N_R
\end{aligned}
\tag{2}
$$

where:

$X_H$, $Y_H$, $N_H$ – hydrodynamic forces and moment acting on the bare hull; $X_P$, $N_P$- force and moment induced by the operation of propellers, $X_R$, $Y_R$, $N_R$ – forces and moment induced by flow around the rudder.

## 2.1 *Hull*

To determine the hydrodynamic forces induced by flow around the hull the following mathematical model was used [3]:

$$
\begin{aligned}
X_H &= -m_x\dot{u} - R_T(u) + X_{vv}v^2 + (X_{vr} + m_y)vr + \\
&\quad + X_{rr}r^2 + X_{vvvv}v^4 \\
Y_H &= -m_y\dot{v} + Y_v v + (Y_r - m_x u)r + Y_{vvv}v^3 + Y_{vvr}v^2 r + \\
&\quad + Y_{vrr}vr^2 + Y_{rrr}r^3 \\
N_H &= -j_{zz}\dot{r} + N_v v + N_r r + N_{vvv}v^3 + N_{vvr}v^2 r + \\
&\quad + N_{vrr}vr^2 + N_{rrr}r^3
\end{aligned}
\tag{3}
$$

where:

$m_x$, $m_y$ – added mass coefficients, in $x$ and $y$ direction; $j_{zz}$ – added inertia coefficient; $R_T(u)$ – hull resistance; $X_{vv}$, $X_{vr}$,..., $Y_v$, $Y_r$,... - coefficient of hydrodynamic forces acting on the hull; $N_v$, $N_r$, ... – coefficients of hydrodynamic moment acting on the hull.

## 2.2 *Rudders*

Hydrodynamic forces induced by rudder laying can be calculated on the basis of equations (4). The model was taken from[4].

$$
\begin{aligned}
X_R &= -(1 - t_R)F_N \sin\delta \\
Y_R &= -(1 + a_H)F_N \cos\delta \\
N_R &= -(x_R + a_H x_H)F_N \cos\delta
\end{aligned}
\tag{4}
$$

where:

$t_R$ - coefficient of additional drag; $a_H$ - ratio of additional lateral force; $x_R$ – x-coordinate of application point of $F_N$; $x_H$ - x-coordinate of application point of additional lateral force; $\delta$ rudder angle; $F_N$ – normal hydrodynamic force acting on the rudder.

The value of normal force $F_N$ was determined on the basis of model (5).

$$
\begin{aligned}
F_N &= 0,5\cdot\rho A_R C_N U_R^2 \\
U_R^2 &= \left(1-w_R\right)^2 (1+C\cdot g(s)) \\
g(s) &= \eta K \frac{\left(2-(2-K)\cdot s\right)s}{\left(1-s\right)^2} \\
\eta &= \frac{D}{h_R} \\
K &= 0.6\frac{1-w_P}{1-w_R} \\
s &= 1-(1-w_P)U\frac{\cos\beta}{n\cdot P} \\
w_R &= w_{R0}\frac{w_P}{w_{P0}} \\
\alpha_R &= \delta-\gamma\cdot\beta_R' \\
\beta_R' &= \beta-2x_R'\cdot r'
\end{aligned}
\tag{5}
$$

where:

$\rho$ – water density; $A_R$ – rudder area; $C_N$ – normal force coefficient; $U_R$ - effective rudder inflow velocity; $C$ – coefficient, dependent on ruder angle sense ($C\approx1.0$); $D$ – propeller diameter; $h_R$ – height of rudder; $w_P$ - wake fraction at propeller location; $w_R$ - wake fraction at rudder location; $w_{R0}$ - effective wake fraction at rudder location, in straight ahead ship motion; $U$ – total velocity of vessel; $\beta$ – drift angle; $n$ – rotational speed of propeller; $P$ – propeller pitch; $x'_R$ – non-dimensional x-coordinate of application point of $F_N$; $r'$ – non-dimensional yaw rate.

### 2.3 *Propellers*

This paper uses a mathematical model of hydrodynamic forces generated by two propellers.

$$
\begin{aligned}
X_P &= (1-t)(T_1+T_2) \\
N_P &= (1-t)(T_1-T_2)d
\end{aligned}
\tag{6}
$$

where:

$t$ - thrust deduction factor; $T_1,T_2$ – thrust generated by propellers; $d$- distance from the axis of propeller to symmetry plane of the vessel, in $y$ direction.

Propeller thrust was determined on the basis of the relation (6).

$$
\begin{aligned}
T &= n^2 D^4 K_T(J) \\
K_T(J) &= a_0 + a_1 J + a_2 J_2 \\
J &= U\cos\beta_P\frac{1-w_P}{nD} \\
w_P &= w_{P0}\cdot\exp(-4.0\beta_P^2) \\
\beta_P &= \beta - x_P'\cdot r'
\end{aligned}
\tag{7}
$$

where:

$T$ – propeller thrust; $J$ - advance coefficient; $a_0$, $a_1$, $a_2$ – $K_T$ polynomial coefficients; $w_{P0}$ - effective wake fraction in straight ahead ship motion; $x'_P$ – non-dimensional x-coordinate of propeller..

Values of thrust coefficients used in the calculations were derived from experimental research.

## 3 DETERMINING OF HYDRODYNAMIC COEFFICIENTS

### 3.1 *The coefficients of the hydrodynamic forces acting on the hull*

The model of the hydrodynamic forces described in section 2.1 requires knowledge of the values of hydrodynamic coefficients: $X_{vv}$, $X_{vr}$,..., $Y_v$, $Y_r$,..., $N_v$, $N_r$, .... The literature, including [5], describes the empirical formulas derived for marine ships. Due to the complicated nature of these forces, the results can be insufficiently accurate. For this reason, preference is given to other, more accurate method to determine the coefficients of hydrodynamic forces. One of these methods is the CFD calculation. In addition to the providing accurate results, numerical calculations enable the model to take into account specific operational conditions of the inland ship, for example, that the impact of shallow water on the hydrodynamic forces acting on the hull.

o determine the coefficients of hydrodynamic interactions it is necessary to have a database containing the values of the hydrodynamic forces and the corresponding to them values of velocity $(u,v,r)$ and the acceleration $(\dot{u},\dot{v},\dot{r})$ of the ship. One way to obtain such a database is to simulate with help of CFD software the series of tests (manoeuvres): yaw , yaw with drift, sway test. Figure (2) shows the trajectory of a ship during these manoeuvres.

The values of the added mass ($m_x$ ,$m_y$,) coefficients , added inertia ($j_{zz}$) coefficient and the ship resistance ($R_T(u)$) can be obtained on the basis of empirical methods or CFD calculations.

During the yaw manoeuvre the ship transverse velocity $v$ and acceleration $\dot{v}$ are zero. The equations of the hydrodynamic forces acting on the hull can be simplified to the following form:

$$
\begin{aligned}
X_H &= -m_x\dot{u} - R_T(u) + X_{rr}r^2 \\
Y_H &= -m_x ur + Y_r r + Y_{rrr}r^3 \\
N_H &= -j_{zz}\dot{r} + N_r r + N_{rrr}r^3
\end{aligned}
\tag{7}
$$

In the results of CFD simulation of the yaw manoeuvre the relation between hydrodynamic forces and moment ($X_H$, $Y_H$ , $N_H$) and velocity $u$, $r$, and acceleration $\dot{u}$ is obtained. The least squares method can be used on the results from yaw simulation to approximate the following coefficients: $X_{rr}$, $Y_r$, $Y_{rrr}$, $N_r$, $N_{rrr}$ .

During the sway manoeuvre the speed $r$ and the acceleration $\dot{r}, \dot{u}$ are zero. The equations of hydrodynamic forces acting on the hull can be simplified to the following form:

$$\begin{aligned} X_H &= -R_T(u) + X_{vv}v^2 + X_{vvvv}v^4 \\ Y_H &= -m_y\dot{v} + Y_v v + Y_{vvv}v^3 \\ N_H &= N_v v + N_{vvv}v^3 \end{aligned} \tag{8}$$

When simulating the sway manoeuvre using CFD the data showing the relation between hydrodynamic forces acting on the hull ($X_H$, $Y_H$, $N_H$) and velocities $u$ and $v$ is obtained. The least squares method is used on the results from sway simulation to approximate the following coefficients: $X_{vv}$, $X_{vvvv}$, $Y_v$, $Y_{vvv}$, $N_v$, $N_{vvv}$.

The CFD simulation of the yaw with drift manoeuvre provides the calculations for the rest of hydrodynamic coefficients: $X_{vr}$, $Y_{vvr}$, $Y_{vrr}$, $N_{vvr}$, $N_{vrr}$.

More information about determining hydrodynamic coefficients can be found[6]

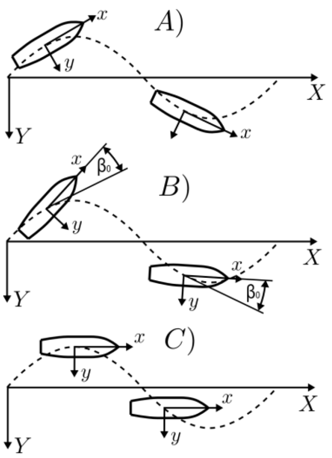


Figure 2. The manoeuvres for determining the hydrodynamic coefficients: A) yaw manoeuvre B) yaw with drift, C) sway manoeuvre.

## 3.2 *Rudder characteristic.*

A mathematical model of hydrodynamic forces acting on the rudders, described in section 2.2, requires knowledge of the normal force coefficient ($C_N$) . The characteristics of isolated rudders have been described in many sources, for example [7]. Working conditions of rudders installed under the hull of the inland vessels may be significantly different than these from a single rudder. This is due to the presence of wake and propeller streams as well as the impact of the limited depth of the waterway. In order to determine the correct characteristics of the rudder, more accurate methods should be used.

In studies to determine the characteristics of the rudders CFD methods were used. The calculations were carried out in two ways. Firstly, the approach shown in Figure 3, was based on calculations of a rudder located in the propeller stream. The geometry of propeller was replaced by the disk with a pressure jump. The value of the pressure jump was equivalent to propeller thrust. Restriction of flow around a rudder at the top and bottom edge was simulated by two flat plates. The symbols *c* and *d* on the scheme denotes distance between rudder and plates. The main advantage of this approach is the low complexity of the discrete model, which significantly accelerates the calculations.

The second method used in the study was to build a full geometric model of the entire hull with propellers and rudders. This solution required the usage of discrete models with a much larger number of elements. CFD calculations of the entire hull give more accurate results but require large computing power. Figure 4 shows an example of a discrete model of the stern of the ship with the rudders and simplified models of propellers.

Additional information on the rudder force numerical calculations can be found in [8].

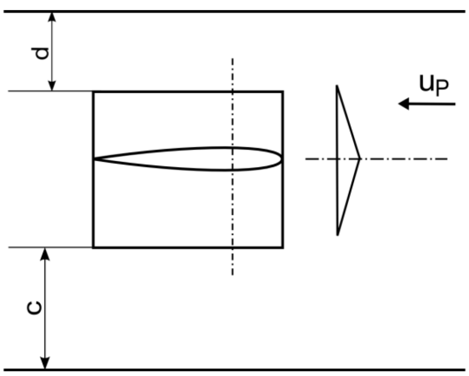


Figure 3. Scheme of model for rudder force calculations.

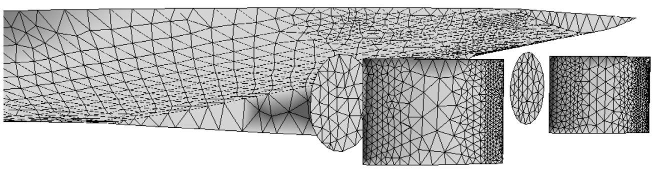

Figure 4. Example of discrete model of the stern of the ship with propellers and rudders.

## 4 CFD METHODS

In the studies the Ansys Fluent commercial CFD software was used. It is based on a finite volume method. To solve the three-dimensional turbulent flow the RANS method was used. The turbulence model *k-ε-Realizable* was used. The boundary layer was calculated using the *Enhanced Wall Treatment* model. The result of research presented in [9] shows that this model works best for flows with large pressure gradients and a separation phenomenon.

The calculations mainly used a structured mesh with hexagonal elements. Unstructured (tetragonal) grids were only used in the calculation of the hull with rudders and propellers, due to the complicated geometries involved.

To simulate the yaw, yaw with drift, sway manoeuvre the moving mesh technology was technique was utilised. Parameters of mesh motion were defined in an additional batch program (UDF) to the system Ansys Fluent (UDF). The program is written in C language.

## 5 RESULTS

Numerical calculations were performed for a model of inland transport vessel (ship A). The scale model was $\lambda = 21.81$.

For the same scale a physical model was created and tests in the towing tank were performed. All tests were performed in the shallow water. In this paper the results for h/T=1.89 are presented. Table 1 contains the main parameters of the ship A.

Table 1. The main parameters of the ship A

| Parameter | unit | ship | value |
|---|---|---|---|
| LPP | m | 85.50 | 3.920 |
| B | m | 11.45 | 0.525 |
| T | m | 2.65 | 0.122 |
| CB | - | | 0.0853 |
| LCB | m | 43.71 | 2.004 |
| Number of propellers | - | | 2 |
| Number of rudders | - | | 2 |

Parameters of the propeller (model)

| Parameter | unit | value |
|---|---|---|
| D | m | 0.08 |
| P/D | - | 1.1102 |
| $A_E/A_0$ | - | 0.7474 |
| Z | - | 4 |

Parameters of the rudder (model)

| Parameter | unit | value |
|---|---|---|
| $h_R$ | m | 0.092 |
| $A_R$ | $m^2$ | 0.0103 |
| Profile | - | NACA0012 |

### 5.1 *Direct Comparison*

CFD calculations are characterized by a number of restrictions and simplifying assumptions. In the numerical calculations of yaw, yaw with drift and sway test, which are necessary for determining the value of hydrodynamic coefficients, a problem with calculation stability occurred . After disabling two-phase flow (air-water) the problem disappeared. Therefore, the calculation of coefficients of hydrodynamic forces acting on the hull $X_H$, $Y_H$, and $N_H$ does not include the impact of the free surface. This problem didn't appear in the calculation of the resistance of the ship. In the subsequent research only situations with low ship speed (Fr = 0.12) were analysed. When the ship speed is relatively low the influence of free surface on the hydrodynamic force is negligible.

The figures 5,6,7 shows a comparison of results obtained from CFD calculations and the experimental test performed in the towing tank. The charts show the course of the hydrodynamic forces $X_H$, $Y_H$ and hydrodynamic moment $N_H$ during the yaw and sway test. During the tests in towing tank the PMM mechanism was used. The worst comparison between CFD and experiment is for $X_H$. This force is relatively small and it is very susceptible for different factors and disturbances. The comparison for hydrodynamic moment $N_H$ is much better. The hydrodynamic moment depends mainly on huge difference of pressure on both sides of a hull. And the pressure field was accurately predicted by CFD calculations.

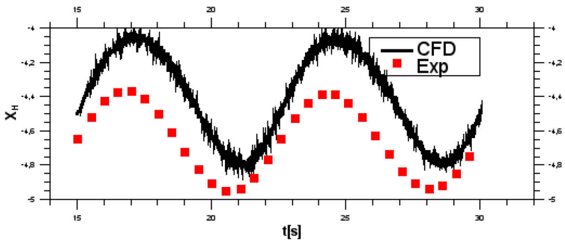


Figure 5. Comparison of the results of the experiment and CFD calculations for the characteristic of $X_H$ forces obtained during yaw test.

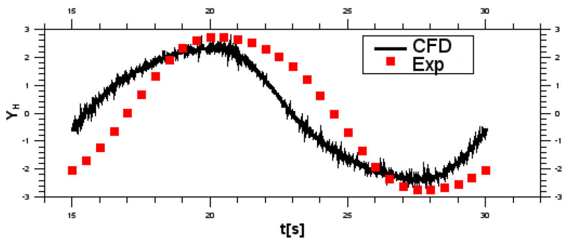


Figure 6. Comparison of the results of the experiment and CFD calculations for calculations for $Y_H$ force obtained during yaw test.

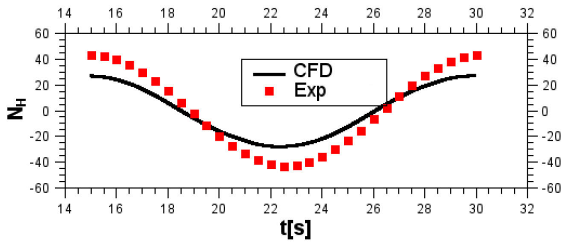


Figure 7. Comparison of the results of the experiment and CFD calculations for the $N_H$ moment obtained during the sway test.

### 5.2 *Indirect Comparison*

In the towing tank the model tests of ship A were performed. The following tests were performed: yaw, yaw with drift and sway. On the basis of the experimental results the coefficients of hydrodynamic forces were calculated. Similarly, on the basis of the CFD calculations the results of a second set of hydrodynamic forces coefficients was determined. For both sets of coefficients the simulation of standard manoeuvres was performed.

The manoeuvre results were obtained from the author's program to simulate the motion of the ship.

The following figures show the comparison of the results obtained from experimental tests and computer simulation. The figures 8,9,10 illustrate the characteristic charts for the turning circle manoeuvre, evasive action and spiral test.

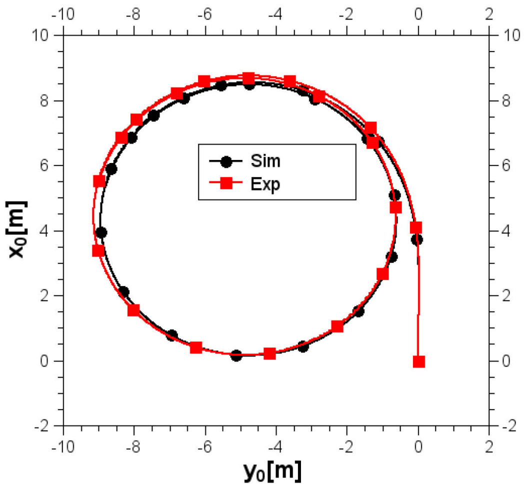


Figure 8. Comparison of trajectory for turning circle manoeuvre, rudder δ = 35 °.

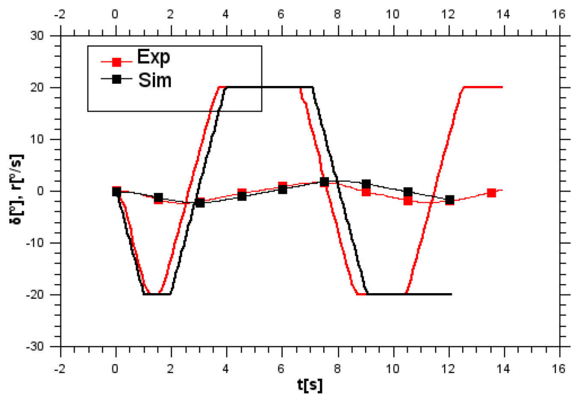


Figure 9. The comparison of characteristic chart of the evasive action.

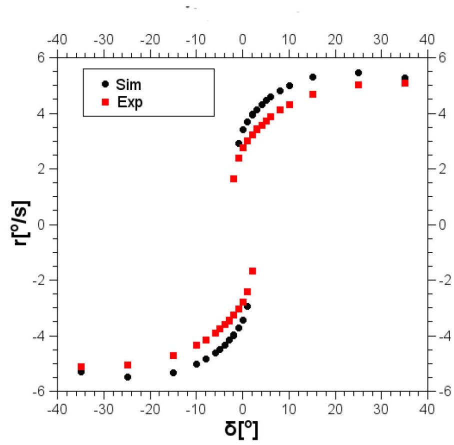


Figure 10. The comparison of characteristic chart of the spiral test.

## 6 SUMMARY

The paper presents a numerical method for evaluating manoeuvring characteristics. Research on a model of the inland vessel showed good agreement between numerical calculations and experimental results.

Due to problems with the stability of the CFD code only the mono-fluid calculations were performed. Further studies will be carried out to calculate the free surface effects, and taking into account phenomena such as sinkage and trim.

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