COEFFICIENT IDENTIFICATION FOR SHIP MANOEUVRING SIMULATION MODEL BASED ON OPTIMIZATION TECHNIQUES

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Abstract. The frequency of ship grounding and collisions led to model the various factors involved during the course of a maneuvering ship. Among these factors are the ship hydrodynamic forces, the ship propulsion forces and forces due to the environmental conditions and the effects of confined water. This paper presents an approach for the identification of coefficients for a free-running ship. We elaborated a ship manoeuvring simulation model with a numerical procedure based on the coupling of optimization techniques and a ship motion simulation model. To identify the hydrodynamic coefficients, an automatic approach is proposed with two main steps: firstly, a sensitivity analysis to identify the most sensitive coefficients; secondly, optimization techniques to calculate their optimal value. Our model has been validated by using experimental data of Esso Bernicia Tanker (190000dwt) for the Turning Circle Test.

1 INTRODUCTION

Many equations of ship motion have been studied to describe the external forces acting on a ship. These external forces or hydrodynamic forces are function of many hydrodynamic coefficients. Abkowitz [8] proposed a hydrodynamic force model based on the multiple polynomial equations of ship manoeuvring variables from Taylor expansion. In this model, the derivatives of hydrodynamic forces with respect to each manoeuvring variables are named the hydrodynamic coefficients. Since, many mathematical models of ship motion have proposed to identify the hydrodynamic coefficients [1], [13], [14], [5],[4], [6]. Several methods identify the hydrodynamic coefficients, such as the captive model test, strip theory, empirical formulae, computational fluid dynamics (CFD), system identification (SI), optimization technique, etc. Among them the system identification and optimization technique are practical and widely used to avoid the scaling effect between the real ship and the scale model [10].

In respect of the system identification (SI), Hwang [12] applied the state augment of Extended Kalman Filtering (EKF) technique to identify the dynamic system of a manoeuvring ship. The slender body theory is utilized to explain the intrinsic nature of cancelation effect for dynamics of ship motion.

Recently, H.K. Yoon and K.P. Rhee [10] applied the Estimation-Before-Modeling (EBM) technique for hydrodynamic coefficients identification. EBM is the two-step method, based on the Extended Kalman Filtering (EKF) technique and Modified-Bryson-Frazier (MBF) smoother to estimate motion variables, hydrodynamic forces, speed and direction of current.

Regarding to the optimization technique, M. Viviani et al. [11] applied the numerical optimization techniques to hydrodynamic coefficients identification from standard manoeuvres (specified by IMO) for a series of twin-screw ships. From regression formulae based on existing ship model-test data, they developed hydrodynamic coefficients identification for non-conventional ships exceeding the parametric range of the experimental data base. By means of a sensitivity analysis, they identified the 5 most sensitive coefficients that their influence is much stronger than remaining coefficients. The objective function represents discrepancies between simulated and experimental manoeuvres, evaluated a sum of relative errors of a series of macroscopic manoeuvring parameters in Turning Circle test and ZigZag test. Optimization procedure is carried out by applying a Multi Objective Genetic Algorithm (MOGA).

To reach a more accuracy of ship simulation trajectory based on the optimization techniques, we have focused analyzing the sensibility of hydrodynamics coefficients in the alternative manoeuvring tests. The objective is to find more the sensible hydrodynamic coefficients, that means the number of identified coefficient is increased. In this study, we carried out an optimization procedure for 10 most sensible coefficients.

2 SHIP MANOEUVERING SIMULATION MODEL

2.1 Ship motions and manoeuvring tests

In the present study, the ship's motions were simulated in 3DOF, are presented in Fig. 1, including surge (along OX), sway (along O_0Y_0) and yaw (along O_0Z_0). The moving coordinate frame $GX_0Y_0Z_0$ is fixed to the ship's gravity center (G) is called the body-fixed reference frame or ship-fixed frame. The coordinate frame $OXYZ$ is called the earth-fixed reference frame [7].

where: $U = ui+vj$: ship velocity; i, j: unit vectors along the $GX_0$and GY_0; ψ: heading angle; $r = \frac{d\psi}{dt}$: yaw angular velocity

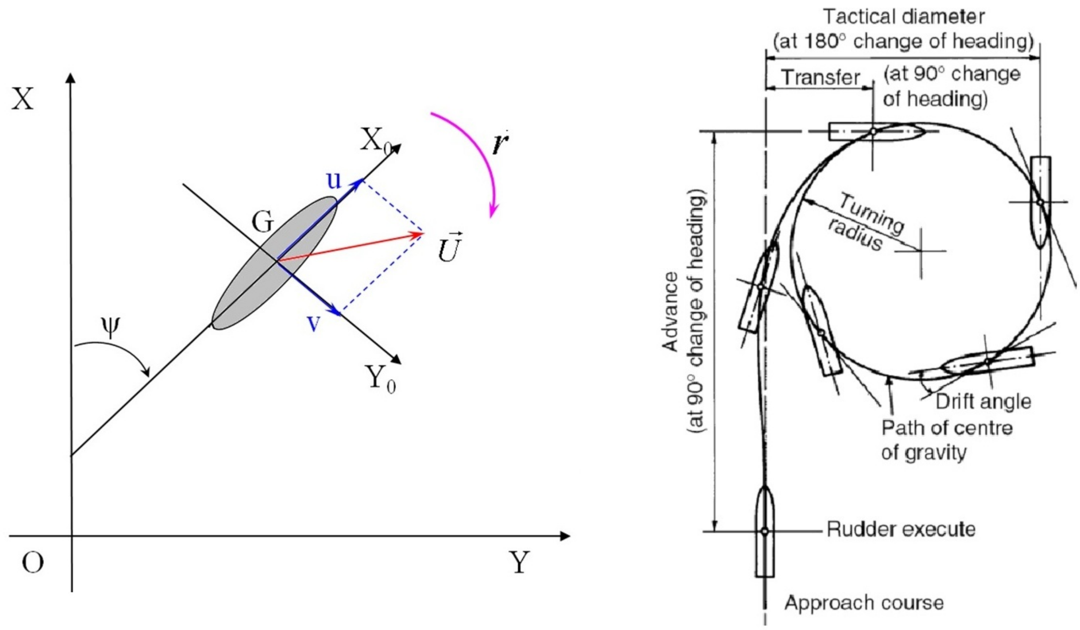

Figure 1: Ship motions in 3DOF and Turning Circle test

The main manoeuvring tests of ship are recommended by the Manoeuvring Trial Code of ITTC and the IMO [9], including: Turning circle test, Spiral manoeuvres, Pull-out manoeuvre, Zigzag manoeuvre, Stopping trial, Hard rudder test and Man-overboard manoeuvre.

In the present study, due to limited number of experimental data, only the Turning Circle test was applied to validate for the Esso Bernicia Tanker (Esso 190000dwt) model.

Turning circle test[9] Starting from straight motion at constant speed, the rudder is turned at maximum speed to an angle δ and kept at this angle, until the ship has performed a turning circle of at least 540^0. The essential information obtained from this

Parameter	Value	Unit
Length between perpendicular (L_{pp})	304.8	m
Beam (B)	47.17	m
Draft to design waterline (T)	18.46	m
Displacement (∇)	220000	m^3
L_{pp}/B	6.46	-
B/T	2.56	-
Block coefficient (C_B)	0.83	-
Design speed (U_0)	16	knots
Nominal propeller (n)	80	rpm

Table 1: Parameters of Esso Bernicia model

manoeuvre consists of (Fig. 1): Tactical diameter, Maximum advance, Transfer at 90^0 change of heading, Times to change heading $90^0$and 180 and Transfer loss of steady speed.

2.2 The Esso Bernicia Tanker (Esso 190000dwt) model

Parameters of the Esso Bernicia Tanker model Mathematical models describing the maneuverability of large tanker in deep and confined waters are found by Van Berlekom and Goddard (1972). One of these models is the Esso Bernicia Tanker (Esso 19000 dwt) [7], with the ship parameters is presented in Tab. 1.

3 DOF motion equations of the Esso Bernicia Tanker model The 3DOF equations of ship motion in Bis-System are given by Van Berlekom and Goddard[7]:

$$\begin{aligned} \dot{u} - vr &= g.X^{"} \\ \dot{v} + ur &= g.Y^{"} \\ \left(L.k_z^{"}\right)^2 \dot{r} &= g.L.N^{"} \end{aligned} \tag{1}$$

with:

$$g.X^{''} = X^{''}_{\dot{u}}.\dot{u} + \frac{1}{L}.X^{''}_{u|u|}.u\,|u| + \frac{1}{L}.X^{''}_{vr}.vr + \frac{1}{L}.X^{''}_{vv}.v\,|v| + \frac{1}{L}.X^{''}_{c|c|\delta\delta}.c\,|c|\,\delta^2 + \tag{2}$$

$$+\frac{1}{L}.X^{''}_{c|c|\beta\delta}.c\,|c|\,\beta\delta + g.T\,(1-t) + \frac{1}{L}.X^{''}_{\dot{u}\xi}.\dot{u}\xi + \frac{1}{L}.X^{''}_{|u|u\xi}.\,|u|\,u\xi + \frac{1}{L}.X^{''}_{vr\xi}.vr\xi + \frac{1}{L}.X^{''}_{vv\xi\xi}.v^2\xi^2$$

$$g.Y^{''} = Y^{''}_{\dot{v}}.\dot{v} + \frac{1}{L}.Y^{''}_{uv}.uv + \frac{1}{L}.Y^{''}_{|v|v}.\,|v|\,v + \frac{1}{L}.Y^{''}_{|c|c\delta}.\,|c|\,c\delta + \frac{1}{L}.Y^{''}_{ur}.ur + \frac{1}{L}.Y^{''}_{|c|c|\beta|\beta\delta}.\,|c|\,c\,|\beta|\,\beta\delta + \tag{3}$$

$$+Y^{''}_{T}.g.T + \frac{1}{L}.Y^{''}_{ur\xi}.ur\xi + \frac{1}{L}.Y^{''}_{uv\xi}.uv\xi + Y^{''}_{\dot{v}\xi}.\dot{v}\xi + \frac{1}{L}.Y^{''}_{|v|v\xi}.\,|v|\,v\xi + \frac{1}{L}.Y^{''}_{|c|c|\beta|\beta\delta\xi}.\,|c|\,c\,|\beta|\,\beta\delta\xi$$

$$g.L.N^{''} = \frac{1}{L^2}.N^{''}_{\dot{r}}.\dot{r} + \frac{1}{L^2}.N^{''}_{uv}.uv + \frac{1}{L}.N^{''}_{|v|r}.\,|v|\,r + \frac{1}{L^2}.N^{''}_{|c|c\delta}.\,|c|\,c\delta + \tag{4}$$

$$+\frac{1}{L}.N^{''}_{ur}.ur + \frac{1}{L^2}.N^{''}_{|c|c|\beta|\beta\delta}.\,|c|\,c\,|\beta|\,\beta\delta + \frac{1}{L}.N^{''}_{T}.g.T + \frac{1}{L}.N^{''}_{ur\xi}.ur\xi +$$

$$+\frac{1}{L^2}.N^{''}_{uv\xi}.uv\xi + N^{''}_{\dot{r}\xi}.\dot{r}\xi + \frac{1}{L}.N^{''}_{vr\xi}.vr\xi + \frac{1}{L^2}.N^{''}_{|c|c|\beta|\beta|\delta|\xi}.\,|c|\,c\,|\beta|\,\beta\,|\delta|\,\xi$$

where $X^{''}, Y^{''}, N^{''}$ are the non-dimensional forces and moments

$k_z^{"} = \frac{1}{L}\sqrt{\frac{I_z}{m}}$ is the non-dimensional radius of gyration

$X_{\dot{u}}^{''}, X_{u|u|}^{''}, .., Y_{\dot{v}}^{''}, Y_{uv}^{''}, ..., N_{\dot{r}}^{''}, N_{uv}^{''}, ..., N_{|c|c|\beta|\beta|\delta|\xi}^{''}$ are the non-dimensional derivatives of ship hydrodynamic coefficients in Bis-System, which will be identified by optimization techniques.

3 OPTIMIZATION ALGORITHMS

In the present study, the multi-variable optimization problems [15] was applied for ship hydrodynamic coefficient identification, derives in 2 options:

- The constrained optimization problem with the SQP method: Minimize the objective function $Fobj = f(\alpha)$ for $\alpha \in E^n$, subject to $\alpha_{min} \leq \alpha \leq \alpha_{max}$.

where

$\alpha = [\alpha_1, \alpha_2, ..., \alpha_n]^T$ is the vector of ship hydrodynamic coefficients or the vector of variables, n is the number of ship hydrodynamic coefficients,

$\alpha_{min}, \alpha_{max}$ are the minimum and maximum values of estimated hydrodynamic coefficients, are also the inequality constraints of optimization problem.

- The unconstrained optimization problem with the Simplex method and BFGS method: Minimize the objective function $Fobj = f(\alpha)$ for $\alpha \in E^n$. where $\alpha = [\alpha_1, \alpha_2, ..., \alpha_n]^T$ is the vector of ship hydrodynamic coefficients or the vector of variables, n is the number of ship hydrodynamic coefficients.

Objective of ship coefficient identification is to identify the optimal hydrodynamic coefficients so that the ship's computed trajectory (simulated trajectory) approximates the ship's experimental trajectory. The deviation between computed trajectory and experimental trajectory needs to be minimized. So the form of objective function $Fobj$ is below:

$$Fobj = \sqrt{\sum_{i=1}^{N} \triangle S_i^2} \quad (5)$$

$$\triangle S_i^2 = \left(x_i^{cal} - x_i^{exp}\right)^2 + \left(y_i^{cal} - y_i^{exp}\right)^2 \quad (6)$$

where

N is the number of coupled points to be approximated,

$\left(x_i^{cal}, y_i^{cal}\right)$ are the coordinates of the point number i on the ship's computed trajectory,

(x_i^{exp}, y_i^{exp}) are the coordinates of the point number i on the ship's experimental trajectory,

$\triangle S_i^2$ is the square of distance discrepancy between the coupled point number i on the ship's computed trajectory and on the ship's experimental trajectory, is also the function of ship hydrodynamic coefficients $\alpha = [\alpha_1, \alpha_2, ..., \alpha_n]^T$, is presented in Fig. 4.

Input data	Value	Unit
Initial ship's position (x_0, y_0)	(0,0)	m
Initial heading angle (ψ_0)	0	deg
Initial advance velocity of ship (U_0)	5.3	m/s
Initial of rudder angle (δ_0)	0	deg
Maximum rotation velocity of rudder $(\dot{\delta}_{max})$	2.7	deg/s
Initial shaft velocity (n_0)	80	rpm
Shaft velocity command (n_c)	80	rpm
Rudder command (to port side) (δ_c)	-35	deg

Table 2: Input data for Turning Circle test of Esso Bernicia model

4 NUMERICAL OPTIMIZATION PROCEDURE

The numerical procedure is presented in Fig. 2. In this article, only emphasizing two main steps:
(i) Sensitivity analysis to identify the most sensitive coefficients.
(ii) Optimization techniques to calculate the optimal value of these coefficients.

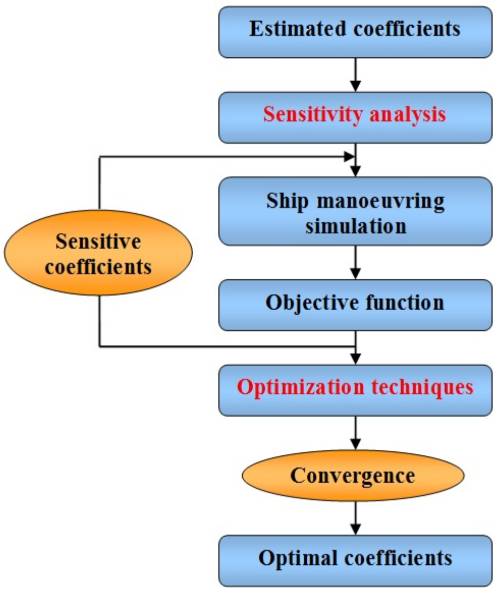

Figure 2: Flowchart of the numerical procedure

In the present study, the numerical model was validated for Esso Bernicia Tanker model in Turning Circle test with the input data presented in Tab. 2.
The numerical procedure starts from all estimated hydrodynamic coefficients in the ship motion equations (Eq. 3, 4 and 5), which will be analyzed by sensitivity analysis. The

analyzing method is to compare the gradient of objective function $Fobj$ while varying the values of each coefficient α_i, so to find coefficients which influence more strongly the gradient of objective function. The 10 most sensitive coefficients (stronger influence coefficients) were chosen among 35 coefficients in ship motion equation with the following condition:

$$\left| \frac{\partial Fobj}{\partial \alpha_i} \right| \geq 0.1 \tag{7}$$

Next, the 10 most sensitive coefficients (optimization variables) are applied the optimization techniques, consisting of SQP, BFGS and Simplex methods. The objective function is normalized by:

$$Fobj^{'}(j) = \frac{Fobj(j)}{Fobj(j=0)} \tag{8}$$

where j is the iteration number of optimization procedure, $j = 0$ is the first iteration, so that the value of $Fobj^{'}(j)$ will be reduced from 1 to an approximate value of 0.

The numerical procedure is repeated until convergence of objective function and variable is reached. Chosen objective function tolerance is 10^{-4}, and the optimization variable one is 10^{-4}.

5 NUMERICAL RESULTS

5.1 Ship trajectory simulation and sensitivity analysis before optimization

Computed and experimental trajectories of ship and sensitivity analysis of ship hydrodynamic coefficients in Turning Circle test (c.f. the experimental data of Esso Bernicia Tanker model [2]) are presented in Fig. 3.

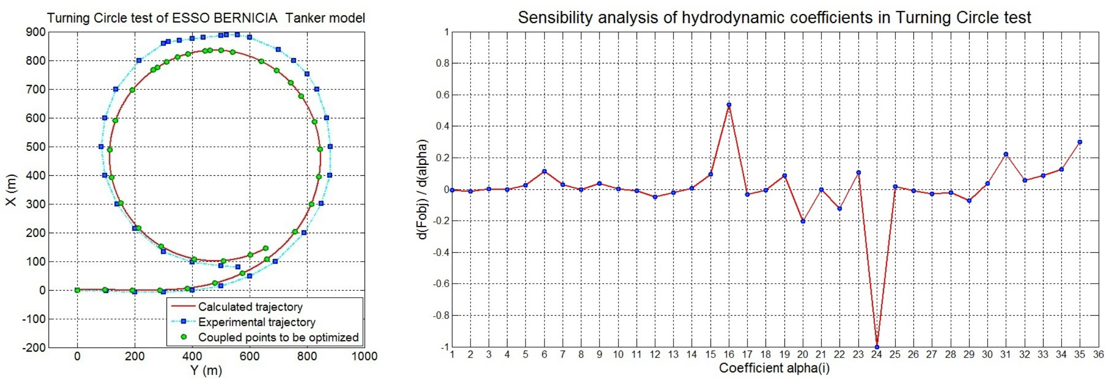

Figure 3: Ship trajectory and sensitivity analysis of ship hydrodynamic coefficients in Turning Circle test

Schematic presentation and value of the deviation between computed and experimental trajectories are presented in Fig. 4.

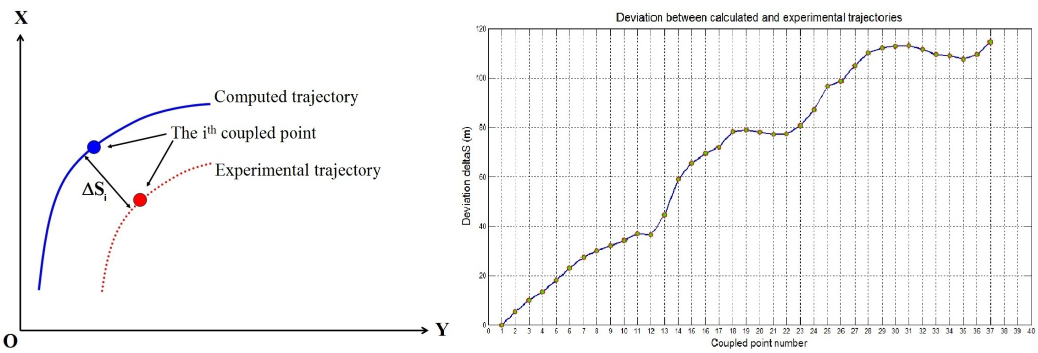

Figure 4: Schematic presentation of the deviation between computed and experimental trajectories

No	Coefficient	Value	No	Coefficient	Value
6	N''_T	-0.02	23	$X''_{c\|c\|\beta\delta}$	0.152
15	$Y''_{ur\xi}$	0.182	24	$N''_{\|c\|c\delta}$	-0.098
16	$N''_{ur\xi}$	-0.047	31	N''_{ur}	-0.207
20	$Y''_{\|c\|c\delta}$	0.208	34	$X''_{\|u\|u\xi}$	-0.0061
22	$N''_{uv\xi}$	-0.241	35	$X''_{c\|c\|\delta\delta}$	-0.093

Table 3: The 10 most sensitive coefficients of Esso Bernicia Tanker model

Average optimal deviation was calculated as below: $\triangle S_{average} = \frac{\sum_{i=1}^{N} \triangle S_i}{N} = 68.0(m)$

The 10 most sensitive coefficients table in Turning Circle test (as condition 7) is presented in Tab. 3.

5.2 Numerical simulation and coefficient identification after optimization

The optimization solution obtained by SQP, BFGS and Simplex methods is presented in Tab. 4

Resolution of 10 optimal hydrodynamic coefficients obtained by SQP, BFGS and Simplex methods is presented in Tab. 5

Method	SQP	BFGS	Simplex
Tolerance of objective function	10^{-4}	10^{-4}	10^{-4}
Tolerance of optimization variables	10^{-4}	10^{-4}	10^{-4}
Number of iterations	29	9	254
Minimum objective function	0.084	0.120	0.085
Average deviation of optimal trajectory (m) $\triangle S_{average} = \frac{\sum_{i=1}^{N} \triangle S_i}{N}$	5.8	8.0	5.8

Table 4: The optimization solutions obtained by SQP, BFGS and Simplex methods

Var	Coeff	Est	Opt (SQP)	Dev(%) (SQP)	Opt (BFGS)	Dev(%) (BFGS)	Opt (Simplex)	Dev(%) (Simplex)
x(1)	N''_T	-0.02	-0.0240	-16.7	-0.0207	-3.5	-0.0184	8.0
x(2)	$Y''_{ur\xi}$	0.182	0.1598	-13.9	0.1822	0.1	0.2113	16.1
x(3)	$N''_{ur\xi}$	-0.047	-0.0416	13.0	-0.0533	-13.4	-0.0462	1.7
x(4)	$Y''_{\|c\|c\delta}$	0.208	0.1761	-18.1	0.2052	-1.3	0.1904	-8.5
x(5)	$N''_{uv\xi}$	-0.241	-0.2823	-14.6	-0.2400	0.4	-0.2329	3.4
x(6)	$X''_{c\|c\|\beta\delta}$	0.152	0.1684	9.7	0.1519	-0.1	0.1902	25.1
x(7)	$N''_{\|c\|c\delta}$	-0.098	-0.0805	21.7	-0.0942	3.9	-0.0820	16.3
x(8)	N''_{ur}	-0.207	-0.2105	-1.7	-0.2096	-1.3	-0.1862	10.0
x(9)	$X''_{\|u\|u\xi}$	-0.0061	-0.0073	-16.4	-0.0065	-6.6	-0.0061	0.0
x(10)	$X''_{c\|c\|\delta\delta}$	-0.093	-0.1000	-7.0	-0.0936	-0.6	-0.1100	-18.3

Table 5: The 10 optimal hydrodynamic coefficients (Var:Variable, Coeff:Coefficient, Est:Estimation, Opt:Optimization, Dev:Deviation)

Optimal trajectory and evolution of objective function obtained by SQP, BFGS and Simplex methods are presented in Fig. 5, Fig. 6, and Fig. 7.

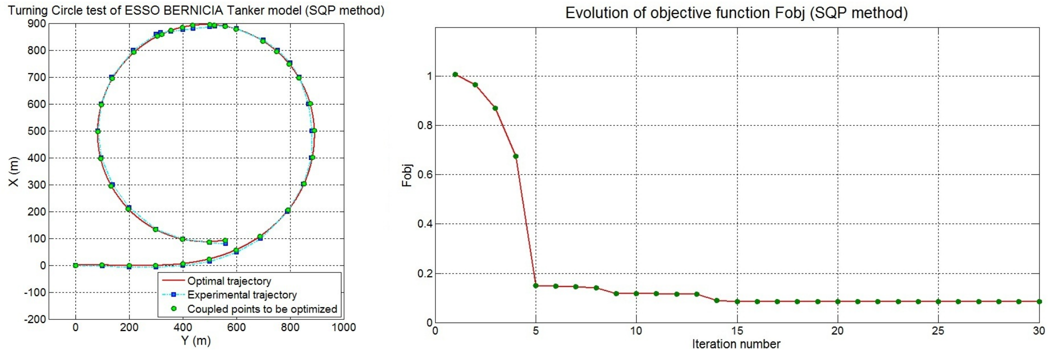

Figure 5: Optimal trajectory and evolution of objective function in Turning Circle test (SQP method)

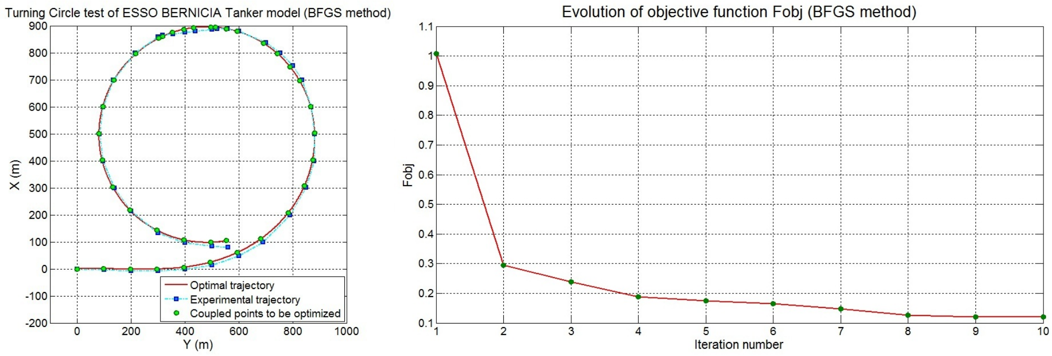

Figure 6: Optimal trajectory and evolution of objective function in Turning Circle test (BFGS method)

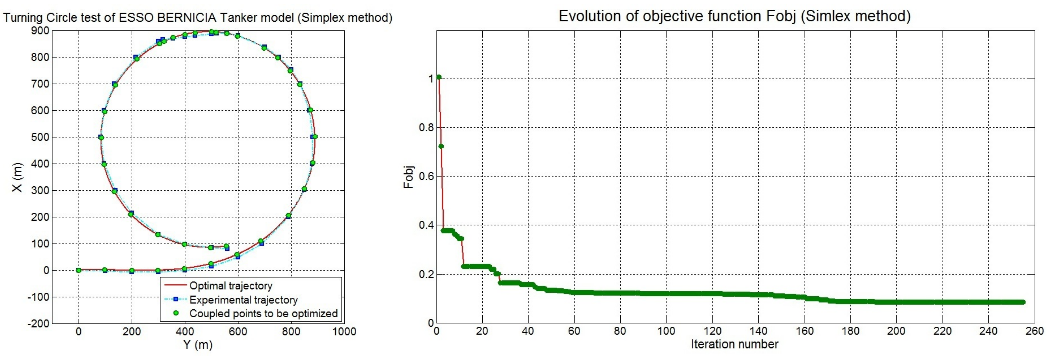

Figure 7: Optimal trajectory and evolution of objective function in Turning Circle test (Simplex method)

As it can be seen in Tab. 4, in the optimization results of SQP method, $Fobj_{min}$ is minimum, $|\triangle S_{average}|$ is also minimum and number of iterations is acceptable. So among these methods, SQP method is the robust method in case of Turning Circle test.

6 CONCLUSIONS

- In the present study, a ship manoeuvring simulation model was elaborated with a numerical procedure based on the coupling of optimization techniques and ship motion simulation. To identify the hydrodynamic coefficients, an automatic approach is proposed with two main steps: firstly, a sensitivity analysis to identify the most sensitive coefficients; secondly, optimization techniques to calculate their optimal value.

- The sensitivity analysis of ship hydrodynamic coefficients is based on the analysis of the gradient of objective function while varying the values of each coefficient, so as to find the most sensitive coefficients. In the step of optimization techniques, the form of objective function was developed and the optimization methods were applied. The optimization techniques are carried out in 2 options of multi-variable optimization problem: The unconstrained optimization problem applying the Simplex method and BFGS method; The constrained optimization problem applying the SQP method.

- Our ship manoeuvring simulation model was validated by using experimental data of Esso Bernicia Tanker model (190000dwt) for the Turning Circle test. The coefficient identification was carried out successfully with a good optimization result. Applying the SQP method to approximate the computed and experimental trajectories, then an averaged optimal discrepancy of 5.8m is obtained. This discrepancy is reduced from a value of 68.0m (before optimization) with a converge was reached after 29 iterations.