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Estimating Hydrodynamic Coefficients with Various Trim and Draught Conditions

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흘수 및 트림 변화를 고려한 선박 유체력 미계수 추정에 관한 연구

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Abstract : *Draught and trim conditions are highly related to the loading condition of a vessel and are important factors in predicting ship manoeuverability. This paper estimates hydrodynamic coefficients from sea trial measurements with three different trim and draught conditions. A mathematical optimization method for system identification was applied to estimate the forces and moment acting on the hull. Also, fast time simulation software based on the Rheinmetall Defense model was applied to the whole estimation process, and a 4,500 Twenty-foot Equivalent Unit (TEU) class container carrier was chosen to collect sets of measurement data. Simulation results using both optimized coefficients and newly-calculated coefficients for validation agreed well with benchmark data. The results show mathematical optimization using sea measurement data enables hydrodynamic coefficients to be estimated more simply.*

Key Words : *Ship manoeuvrability, System identification method, Hydrodynamic coefficients, Sea trial, Mathematical optimization*

요 약 : 선박의 다양한 흘수 및 트림 조건은 조종성능 추정을 위한 중요한 요소 중 하나이다. 본 논문에서는 세 종류의 흘수 및 트림 조건에서의 해상 시운전 자료를 바탕으로 하여 선체 유체력 미계수를 추정하였다. 시스템 식별법(system identification)의 하나인 수학적 최적화(mathematical optimization method) 및 Rheinmetall Defense사의 선박 운동 모델을 적용한 fast time 시뮬레이션 소프트웨어를 이용하여 시운전 항적데이터 및 관련 시뮬레이션 자료를 이용하여 선체 유체력 미계수를 추정하였다. 최적화 된 계수를 적용한 시뮬레이션 결과는 기존 계수 추정식을 사용한 시뮬레이션 결과와 대비하여 해상 시운전 계측 결과와 유사함을 보여주었으며 추가로 진행된 2차 검증 결과에서도 상대적으로 높은 유사함을 확인하였다.

핵심용어 : 조종성능, 시스템 식별, 유체력 미계수, 해상 시운전, 수학적 최적화

1. Introduction

With the development of information technology, ship modelling technology is required to satisfy all ships and navigational conditions. Various loading conditions of a vessel, which also affects draught and trim conditions, is one of the major constraints to determine manoeuvrability. For example, fully loaded vessel requires greater turning circle than the one in ballast condition and trimmed by stern condition has larger circle than even keel condition (Kijima et al., 1990; Oltmann, 2003).

The most reliable way to examine ship's manoeuvrability considering with loading conditions is to conduct the model tests, such as planar motion mechanism, rotating arm and towing tank, or real ship trial for every loading condition. However, it requires expensive time and cost for the experiment (Yoon et al., 2016). IMO standards for ship manoeuvrability consider that and

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require only for full load condition of the vessel, also it is hard to get such data for all ships (Im et al., 2005).

International Towing Tank Conference (ITTC) summarized multiple ways to estimate and to approximate hydrodynamic coefficients for the ship manoeuvrability (ITTC, 2008). Computational methods, such as Computational Fluid Dynamics (CFD) method and system identification method are also an alternative for the model test.

As a preliminary study for estimation of all loading conditions, this paper estimates hydrodynamic coefficients with sets of sea measurement data by mathematical optimization, which is a kind of the system identification method. Based on the authors' previous researches, coefficients are optimized through the Interior point algorithm and these are validated through comparison with the measurement data from sea trial (Kim et al., 2016; Kim et al., 2017).

2. Modelling ship and benchmark data

2.1 Mathematical model

This study applied the 3-Degrees-of-Freedom (DOF) ship-fixed and earth-fixed coordinate systems. Fig. 1 illustrates basic information of the coordinate systems. The Ship-fixed-coordinate $O-xy$ plane and the Earth-fixed-coordinate $O_0-x_0y_0$ plane are placed on the undisturbed free surface, with the x_0 axis pointing in the direction of the original heading of the ship. The z_0 axis and the z axis point downwards vertically. The angle between the directions of the x_0 axis and the x axis is defined as the heading angle, ψ.

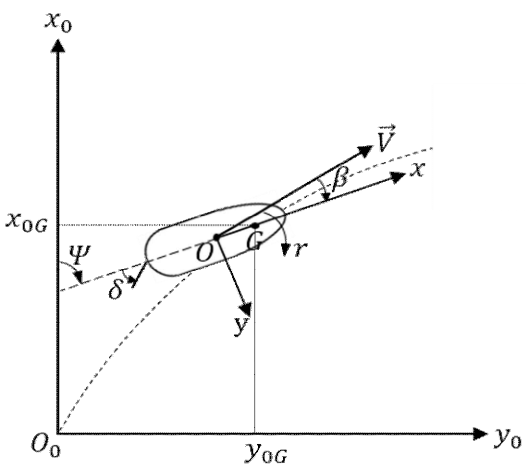

Fig. 1. Coordinate system of the vessel.

where,

G : Center of gravity

Ψ : Heading

β : Drift angle

δ : Rudder angle

$\vec{V}$: Ship's speed

r : yaw rate

A fast time simulation tool SIMOPT with a mathematical model of a Ship Handling Simulator (SHS) systems ANS5000, developed by Rheinmetall Defence Electronics is used for the optimization process (ISSIMS GmbH, 2013). In the mathematical model of the tool, a ship is considered as a massive and rigid body and forces and moment are acting on the hull can be described as equation (1), according to the Newtonian law of motion (Rheinmetall Defence Electronic, 2008).

$$\begin{aligned} X &= m(\dot{u}-vr-x_g r^2) \\ Y &= m(\dot{v}+ur+x_g\dot{r}) \\ N &= I_z\dot{r}+mx_g(\dot{v}+ur) \end{aligned} \tag{1}$$

The model applies modular structure to each force and moment as equation (2): hull, propeller, rudder and other external forces and moments.

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

The hydrodynamic forces and moment acting on the hull are composed as Equation (3) and the empirical regression formulas of Norrbin and Clarke are applied to calculate the initial hydrodynamic coefficients (Norrbin, 1971; Clarke et al., 1983). Each hydrodynamic coefficients can be expressed the function of ship's main dimension as equation (4): length, beam, draught and displacement of the ship. Y_{non} and N_{non} are non-linear components of sway force and yaw moment. These non-linear components vary according to the position of the ship's turning point.

$$\begin{aligned} X_H' &= X_{up}'\dot{u}+X_{vr}'vr+X_{uu}'u|u|+X_{u4}'u^3|u|+X_{uvvv}'uv^2|v| \\ Y_H' &= Y_{vp}'\dot{v}+Y_{rp}'\dot{r}+Y_{ur}'ur+Y_{uv}'|u|v+Y_{non}' \\ N_H' &= N_{rp}'\dot{r}+N_{vp}'\dot{v}+N_{ur}'|u|r+N_{uv}'uv+N_{non}' \end{aligned} \tag{3}$$

$$\left\{Y_{uv}', Y_{ur}', N_{uv}', N_{ur}', Y_{non}', N_{non}'\right\} = f(L, B, T, \triangle) \tag{4}$$

2.2 Benchmark data

A set of benchmark data is acquired from sea trials using a 4,500 TEU class container carrier. Details of the vessel are given in Table 1.

Five zig-zag manoeuvres under three different loading conditions were carried out for this study. Table 2 shows detailed conditions for each manoeuvre.

Table 1. Particulars of benchmark vessel

Type of ship	4,500 TEU Class container carrier
Length overall	294.12 m
Length between perpendicular	283.20 m
Beam	32.20 m
Design draught	12.00 m
Scantling draught	13.00 m
Maximum speed	23.70 knots
Type of main engine	MAN B&W 9K90MC-C
Power	55,890 HP (41,040 KW)

Table 2. Maneouvre conditions of each trial

	Data1	Data2	Data3	Data4	Data5
Manoeuvre	ZZ10P	ZZ10S	ZZ10S	ZZ10P	ZZ20S
Latitude	32.8N	32.0N	10.7N	9.7N	9.7N
Longitude	119.9W	117.3W	67.2W	79.6W	79.6W
Heading(°)	110	110	260	250	250
RPM (‱)	843	620	676	422	422
Draught fore(m)	12.75	12.75	10.00	9.10	9.10
Draught mid(m)	12.55	12.55	10.00	-	-
Draught aft(m)	13.00	13.00	10.00	9.60	9.60
Wind direction(°)	270	310	20	50	50
Wind speed(kts)	12	15	5	15	15
Current direction(°)	160.47	251.56	169.50	23.62	23.62
Current speed(kts)	1.37	0.88	0.28	1.25	1.55
Water depth(m)	>1000	>1000	>1000	>1000	>1000

3. Estimation of hydrodynamic coefficients

3.1 Mathematical optimization

The mathematical optimization is a process to minimize or maximize an objective function value, subject to several constraints on its variables (Nocedal and Wright, 2006). This can be written as equation (5):

$$\min_{x \in R^n} f(x), \text{ subject to} \tag{5}$$
$$c_i(x) = 0, i \in E$$
$$c_i(x) \geq 0, i \in I$$

where,

- x is the variable, which has to be optimized ;
- f is the objective function, a function which returns scalar and it contains the information of minimization or maximization;
- c_i are constraints, which sets equations and inequality condition those the variable x must satisfy during the whole optimization process. The constraints are optional in the optimization process.

Fig. 2 shows the whole process of the mathematical optimization to get tuned hydrodynamic coefficients. The optimization process in the process is carried out by the Optimization Toolbox of MATLAB.

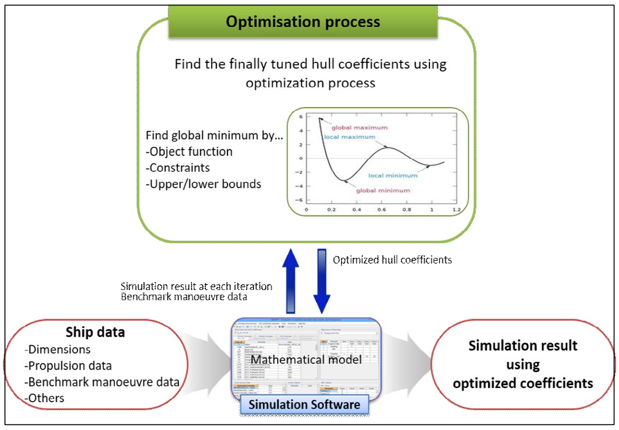

Fig. 2. Concept flow of the coefficient optimization.

The solver requires an objective function, which calculates a minimum or a maximum value of the function. Constraints also can increase the reliability of the optimization results. In this study, lower and upper bound are applied as constraints of the optimization process.

3.2 Sensitivity analysis

A lot of target variables for the optimization process requires expensive resources for the calculation. Therefore this study conducted a sensitivity analysis of each coefficient with the corresponding manoeuvre, prior to the main optimization process.

The procedures of the sensitivity analysis are as follows:

1) Split coefficients into two groups according to the manoeuvre tests: the constant speed with straight motion and zigzag manoeuvre.
2) Conduct manoeuvring simulations with regard to certain changes of a specific coefficient.
3) Get derivative of each data set and conduct min-max normalization for all hydrodynamic coefficients to figure out their own sensitivity in the group.

Fig. 3 and Fig. 4 show the results of sensitivity analysis and Table 3 shows the list of coefficients for the optimization of this study. Stepwise optimization is carried out based on the results of the sensitivity analysis. Two coefficients for the force acting on X-axis is optimized with straight motion with constant speed. Also four linear coefficients for the force acting on Y- and Z-axis is optimized with various zig-zag manoeuvres.

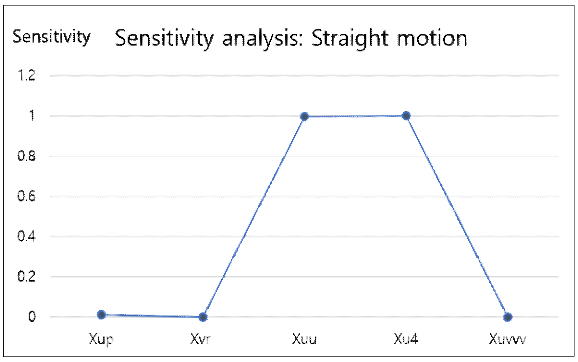

Fig. 3. Result of sensitivity analysis (1): for straight motion.

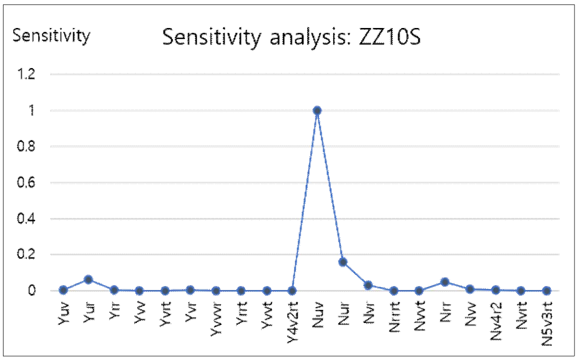

Fig. 4. Result of sensitivity analysis (2): for zig-zag manoeuvre.

Table 3. Detailed conditions of optimization

Optimization Step	Coefficients	Remarks
Step 1	Xuu Xu4	Straight motion
Step 2	Yuv Yur Nuv Nur	Zig-zag manoeuvre

3.3 Optimization conditions

Table 4 shows an example of optimization conditions, a condition for measurement data 3. The initial values of the optimization are calculated by the Clarke estimation and lower and upper bounds are set by values close to 0 for each sign or 10 times the initial values. The object function calculates differences of X and Y coordinates between the benchmark data and the optimized coefficients at each iteration.

Optimizations are carried out only for three data sets, measurement data 2 to 4, which have different trim and draught conditions. Data 1 and data 5 are used for validation of optimization results with corresponding trim and draught.

Table 4. Detailed conditions of optimization for data 3

	Step 1		Step 2	
Solver	fmincon			
Algorithm	interior-point			
Initial values	Xuu	-0.0373	Yuv	-1.3811
	Xu4	-0.4534	Yur	0.3820
			Nuv	-0.4401
			Nur	-0.2348
Lower bounds	Xuu	-0.3700	Yuv	-13.811
	Xu4	-4.5000	Yur	0.0001
			Nuv	-4.4019
			Nur	-2.3480
Upper bounds	Xuu	-0.0001	Yuv	-0.0001
	Xu4	-0.0001	Yur	3.8201
			Nuv	-0.0001
			Nur	-0.0001
Objective function	Track difference			
	straight motion		zigzag 10 degrees	
Linear/Nonlinear Constraints	none		none	

4. Validation of optimization results

4.1 Validation with corresponding benchmarks

Table 5 and Table 6 presents optimization results, coefficients and corresponding manoeuvre characteristics, respectively. Simulation results using Clarke estimation coefficients have a relatively big difference to the benchmark data compared with the simulations results using the optimized coefficients.

Table 5. Optimization results: hydrodynamic coefficients

		Xuu	Xu4	Yuv	Yur	Nuv	Nur
Data 2	C	-0.0280	-0.3405	-1.5857	0.4281	-0.5625	-0.2675
	S1	-0.0250	-0.2865				
	S2			-1.9472	0.3426	-1.2354	-0.2783
Data 3	C	-0.0373	-0.4534	-1.3811	0.3820	-0.4401	-0.2348
	S1	-0.0515	-0.5873				
	S2			-2.2214	0.4827	-3.4181	-0.6116
Data 4	C	-0.0407	-0.4948	-1.3947	0.3934	-0.3965	-0.2339
	S1	-0.0665	-0.4536				
	S2			-2.2611	0.3919	-0.9541	-0.2335
Remarks		C: Clarke estimation S1: Step 1 (Straight motion) S2: Step 2 (Zigzag manoeuvre)					

Table 6. Optimization results: manoeuvre characteristics

		Way/Lpp	Init.	Yaw	Ovst1	Ovst2
Data 2	Clarke	3.33	82	266	1.87	2.73
	Step1	3.52	79	319	1.99	2.55
	Step2	3.52	69	378	5.31	9.66
	Bench	3.53	58	370	6.70	11.80
Data 3	Clarke	5.58	57	272	1.87	2.51
	Step1	5.22	64	286	1.68	2.42
	Step2	5.22	38	265	3.63	7.13
	Bench	5.22	47	279	4.80	7.40
Data 4	Clarke	3.89	89	414	1.71	1.79
	Step1	3.50	93	438	1.53	1.72
	Step2	3.51	87	423	2.98	3.90
	Bench	3.52	78	398	3.20	4.60
Remarks		Bench: Benchmark data (Measured data) Way/Lpp: Distance from start point / Lpp Init. : Initial turning time (s) Yaw : Yaw checking time (s) Ovst1 : First overshoot angle (˚) Ovst2 : Second overshoot angle (˚)				

As seen in Fig. 937 to Fig. 10, Simulation with optimized coefficients made similar heading values to the reference data and this also enables similar trajectory compared to the simulation using Clarke estimation coefficients.

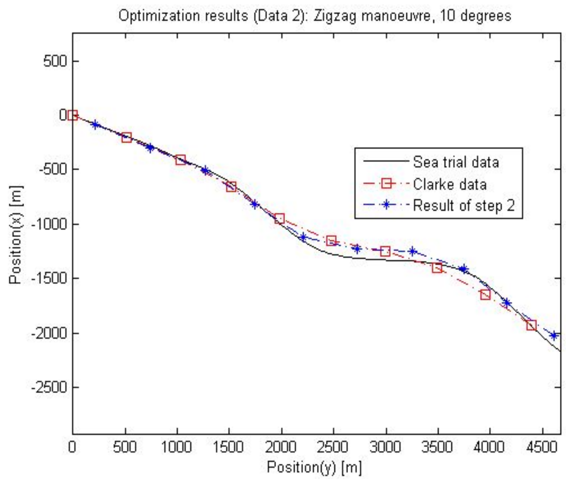

Fig. 5. Trajectory comparisons for Data 2.

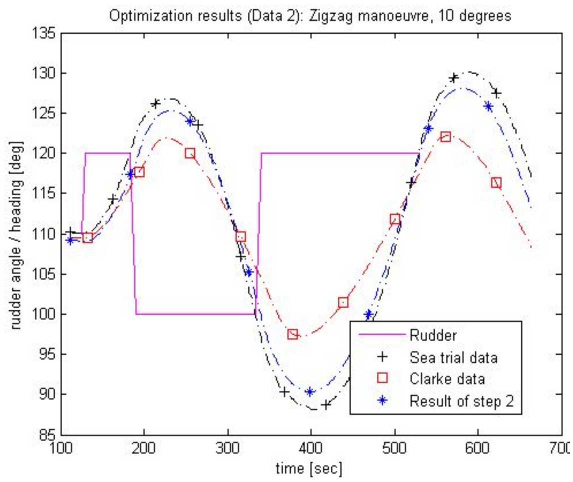

Fig. 6. Heading comparisons for Data 2.

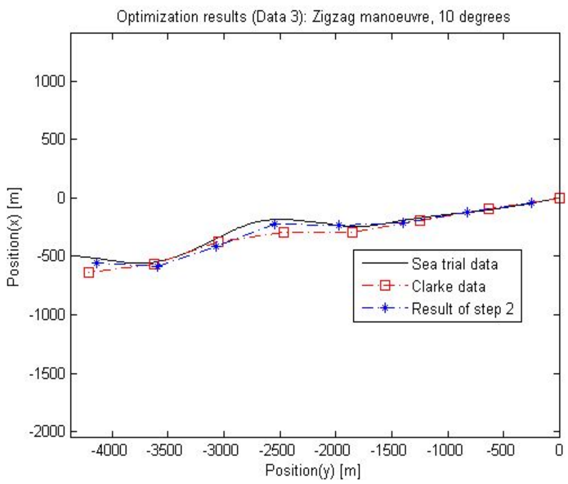

Fig. 7. Trajectory comparisons for Data 3.

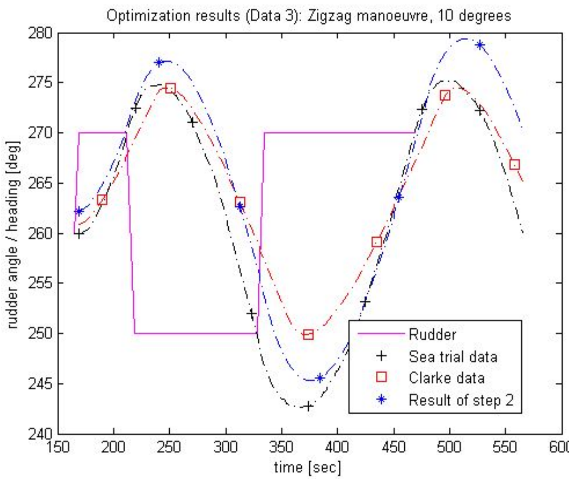

Fig. 8. Heading comparisons for Data 3.

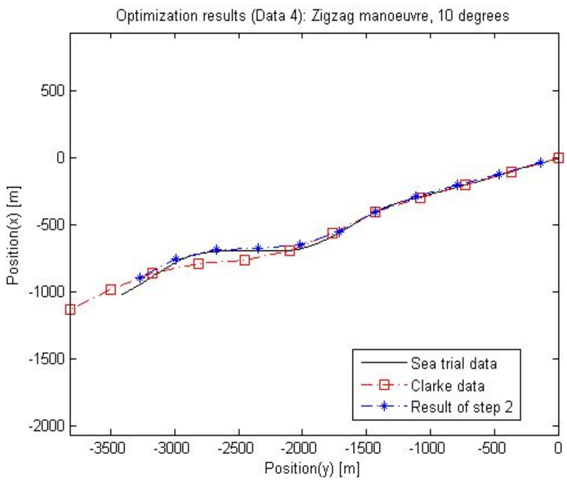

Fig. 9. Trajectory comparisons for Data 4.

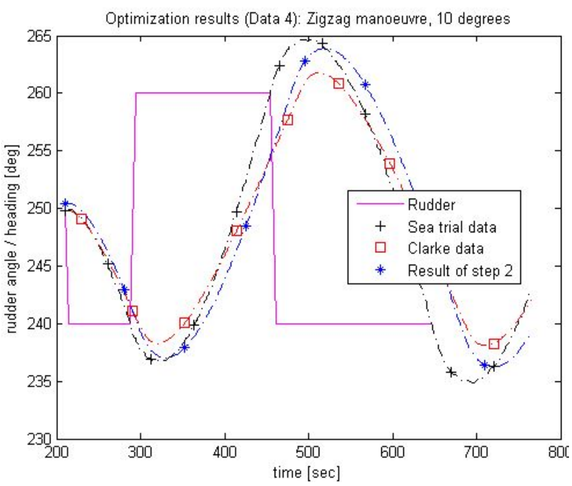

Fig. 10. Heading comparisons for Data 4.

4.2 Validation with other manoeuvre data

An additional validation is carried out with rest manoeuvre measurements. Trajectory and heading records for Data 1 and Data 5 are compared simulation results using coefficients from optimization of Data 2 and Data 4, respectively. Table 7 and Fig. 11 to Fig. 14 presents a comparison between benchmark and simulation results. For Data 1, the second overshoot angle and Way/Lpp are still differed from the benchmark values and these are related to the difference of trajectory between them. Whereas the simulation result for Data 5 is almost similar with the benchmark data even it uses the coefficients optimized from Data 4, which are based on same zig-zag manoeuvre, but different rudder angles.

Table 7. Validation using additional manoeuvres

		Way/Lpp	Init.	Yaw	Ovst1	Ovst2
Data 1	Clarke	4.7	76	267	2.34	2.26
	Val.	4.8	51	278	6.27	8.28
	Bench	4.42	46	293	6.00	12.30
Data 5	Clarke	2.15	93	441	3.21	3.25
	Val.	1.93	84	436	5.59	6.26
	Bench	1.96	81	405	5.60	6.10
Remarks		Val.: Validation using optimization results of Data 2 and Data 4, respectively Bench: Benchmark data (Measured data) Way/Lpp: Distance from start point / Lpp Init. : Initial turning time (s) Yaw : Yaw checking time (s) Ovst1 : First overshoot angle (˚) Ovst2 : Second overshoot angle (˚)				

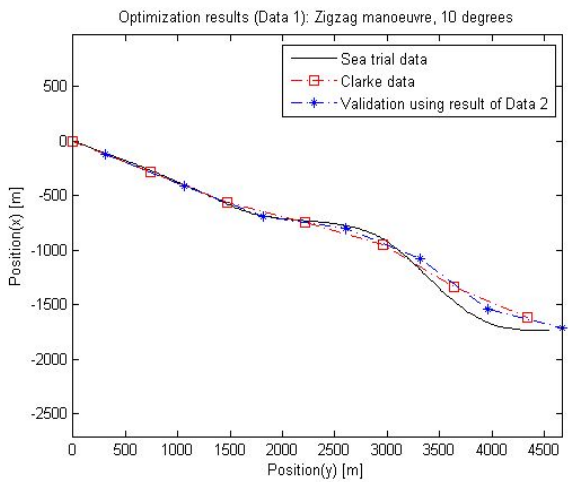

Fig. 11. Trajectory comparisons for Data 1.

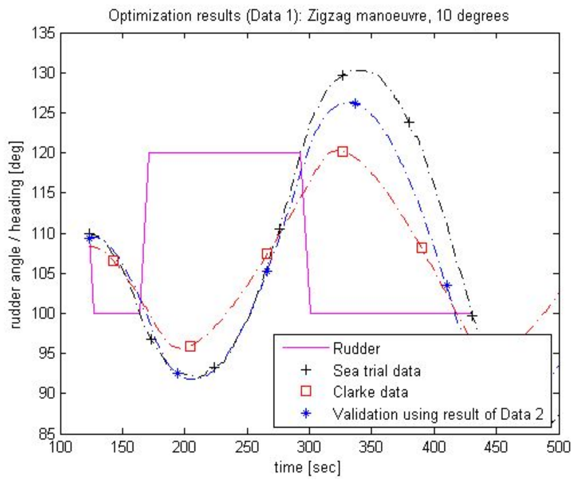

Fig. 12. Heading comparisons for Data 1.

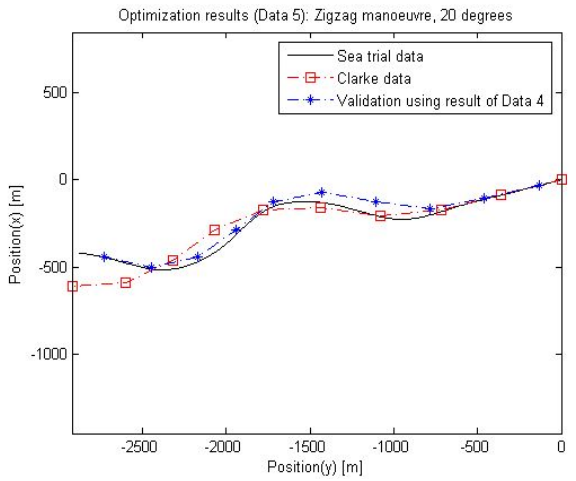

Fig. 13. Trajectory comparisons for Data 5.

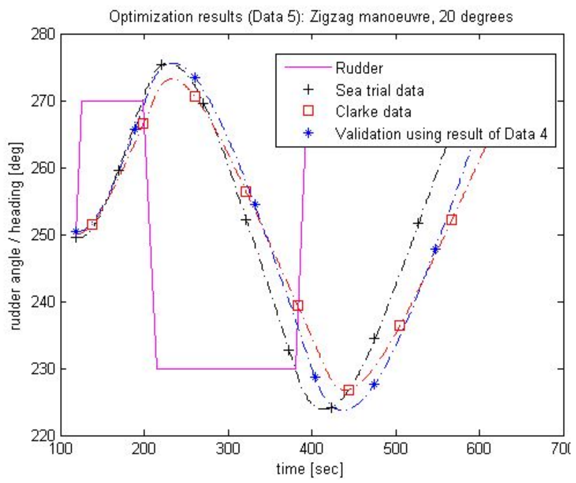

Fig. 14. Heading comparisons for Data 5.

4.3 General review

Two kinds of validations are carried out in this paper. Firstly a comparison among a measurement data, a simulation result using existing coefficient estimation formulas and a simulation result using optimized hydrodynamic coefficients shows that the result using optimized coefficients are relatively similar with the benchmark data than the result using original coefficients. As a second validation, an another measurement data with the same trim draught conditions for the first validation is chosen as a benchmark data. Same as the first validation, the result using optimized hydrodynamic coefficients is similar with the benchmark data. However, additional validations using other manoeuvres, such as turning manoeuvre and emergency manoeuvres, are still required for higher reliabilities of the optimization results.

5. Conclusion

This paper estimated hydrodynamic coefficients for modelling ship under various loading conditions. The mathematical optimization, which is a kind of the system identification method, is applied to calculate the coefficients. Three different loading conditions and in five sea trial measurement data are used for the benchmark data. Also, two kinds of test manoeuvres, straight motion with constant speed and zig-zag manoeuvre, are applied in the optimization process in consideration of measurement data and coefficients to be optimized. The study can be summarized as follows:

1) Simulation results using optimized hydrodynamic coefficients are relatively close to the benchmark data, comparing with the one using the coefficients calculated by the Clarke estimation formulas.

2) For the additional validation, the optimized coefficients agree well with the benchmark data, which is the same loading condition with the original benchmark data.

3) However, due to limitation of data measuring, validations using other manoeuvres except a manoeuvre which is used for the optimization process are not carried out in this paper.

Based on the results of this study, it could be possible to get a new estimation formulas to complement the existing Clarke's formulas in the future studies. In addition, more manoeuvres with various loading conditions and types are still required for higher reliability of the new suggestion.

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