Applied Ocean Research 67 (2017) 9–20

Contents lists available at ScienceDirect

Applied Ocean Research

journal homepage: www.elsevier.com/locate/apor

Measures to diminish the parameter drift in the modeling of ship manoeuvring using system identification

Weilin Luo [a,b,*], Xinyu Li [a]

[a] School of Mechanical Engineering and Automation, Fuzhou University, Fuzhou 350116, China
[b] Fujian Province Key Laboratory of Structural Performances in Ship and Ocean Engineering, Fuzhou 350116, China

ARTICLE INFO

Article history:
Received 10 October 2016
Received in revised form 10 May 2017
Accepted 24 June 2017
Available online 7 July 2017

Keywords:
Ship manoeuvring
System identification
Parameter drift
Regression analysis
Support vector machines

ABSTRACT

System identification provides an effective way to predict the ship manoeuvrability. In this paper several measures are proposed to diminish the parameter drift in the parametric identification of ship manoeuvring models. The drift of linear hydrodynamic coefficients can be accounted for from the point of view of dynamic cancellation, while the drift of nonlinear hydrodynamic coefficients is explained from the point of view of regression analysis. To diminish the parameter drift, reconstruction of the samples and modification of the mathematical model of ship manoeuvring motion are carried out. Difference method and the method of additional excitation are proposed to reconstruct the samples. Using correlation analysis, the structure of a manoeuvring model is simplified. Combined with the measures proposed, support vector machines based identification is employed to determine the hydrodynamic coefficients in a modified Abkowitz model. Experimental data from the free-running model tests of a KVLCC2 ship are analyzed and the hydrodynamic coefficients are identified. Based on the regressive model, simulation of manoeuvres is conducted. Comparison between the simulation results and the experimental results demonstrates the validity of the proposed measures.

1. Introduction

Ship manoeuvrability is one of the most important ship hydrodynamic performances. Prediction of ship manoeuvrability at the design stage has been recommended in the Standards for Ship Manoeuvrability by the International Maritime Organization (IMO) [1]. During the last decade, research on the prediction of ship manoeuvrability has been increasingly paid attention to. Generally, two ways, simulation-free and simulation-based methods, can be used to evaluate the ship manoeuvring performances like advance, transfer, tactical diameter, overshoot angles, time to check yaw [2]. Simulation-free method is a direct method since one can obtain the manoeuvrability parameters directly from database, full-scale trials or free-running model tests. For the simulation-based method, the manoeuvring performances are predicted by means of computer simulation. Compared with simulation-free method, the simulation-based method is preferred in the prediction of ship manoeuvrability due to the development of computer science and techniques. To perform manoeuvring simulation, a ship manoeuvring model is indispensable and the accuracy of the model determines the prediction accuracy. Commonly used ship manoeuvring models include Abkowitz model [3], MMG model [4], and response model [5]. Abkowitz model and MMG model can also be called as hydrodynamic models. No matter which model is employed to predict ship manoeuvring, it is required to determine the model parameters first. For Abkowitz model and MMG model, those parameters are referred to as hydrodynamic derivatives (coefficients) while manoeuvring indices for response model. Although the response model presents a simpler manoeuvring model in which fairly few parameters are contained, in the ship manoeuvrability community an Abkowitz model or a MMG model is usually preferred because they provide a more comprehensive description of ship manoeuvring motion. Nevertheless, it is challenging to accurately determine so many hydrodynamic coefficients in a hydrodynamic model.

Five methods are available to determine the hydrodynamic coefficients in a mathematical model of ship manoeuvring, including database, empirical formula, captive model test, CFD calculation and system identification (SI). Among these, the SI based method provides an effective and practical way. Its main advantages refer to (i) combined with free-running model tests, the cost is relatively low since it is easy to generate more manoeuvres after a first set of model tests; (ii) this method can be applied to either

* Corresponding author at: School of Mechanical Engineering and Automation, Fuzhou University, Fuzhou 350116, China.
E-mail address: wlluofzu@gmail.com (W. Luo).

http://dx.doi.org/10.1016/j.apor.2017.06.008
0141-1187/

model-scale or full-scale manoeuvres [2]. When applied to full-scale trials, the scale effect can be avoided. During last decades, the SI application to the modeling of ship manoeuvring has been continuously studied and many SI schemes have been proposed to derive hydrodynamic coefficients, including least squares (LS) [6,7], model reference method (MRM) [8,9], extend Kalman filter (EKF) [10,11], maximum likelihood (ML) [12,13], recursive prediction error (RPE) [14,15], frequency spectrum analysis (FSA) [16,17], particle swarm optimization (PSO) [18,19], genetic algorithm (GA) [20,21], neural networks (NN) [22,23], and support vector machines (SVM) [24,25]. During the past decade, with the development of experimental and identification techniques, SI based modeling of ship manoeuvring has received increasing attention.

As pointed out, each means to come to manoeuvring predictions has its own advantages and disadvantages [2]. For SI based method, the main difficulty is how to deal with the problem of parameter identifiability. Such an issue can be described from two aspects. First, not all parameters in the manoeuvring model can be obtained using SI, no matter what input–output samples are given and no matter which SI scheme is adopted. Second, parameter drift happens to some hydrodynamic coefficients, which means the obtained coefficients deviate from their true values. For the first kind of parameter identifiability, an effective solution is to determine some hydrodynamic coefficients first in another way instead of SI, such as the slender-body theory, empirical formula, captive model test, or CFD calculation. Afterwards, the remaining hydrodynamic coefficients can be obtained using SI. Usually but not always, the inertia hydrodynamic coefficients, i.e. added masses and added moments of inertia, are selected to be predetermined and satisfactory estimation can be obtained [26–30]. For the second kind of parameter identifiability caused by parameter drift, it is more complicated and challenging. When parameter drift happens, one might obtain a 'deceptive' regressive model. This model can predict some manoeuvre well while fails for the other manoeuvres. The effect of parameter drift nearly always exists when applying SI to derive a ship manoeuvring model. Moreover, this effect is more severe for the identification of a complicated model for instance the Abkowitz model.

To diminish the parameter drift, some measures have been proposed such as parallel processing, exaggerated over- and underestimation, parameter transformation [10,31,32], modification of input scenario [13,33,34], and model simplification by sensitivity analysis [35–37]. Nevertheless, more attention should have been paid to this topic to develop the SI based prediction of ship manoeuvrability. In addition, some issues are supposed to be further addressed, for example the diminishment of drift of nonlinear hydrodynamic coefficients, design of the excitation, the criteria adopted in sensitivity analysis. In this paper, those issues are addressed. Efforts are devoted to the diminishment of the drift of linear and nonlinear hydrodynamic coefficients in an Abkowitz model. The reasons for parameter drift are accounted for. Several measures to diminish the parameter drift are presented, including two measures to reconstruct the data samples, and a measure to modify the mathematical model of ship manoeuvring motion as well. Combined with the diminishment measures, SVM based SI is employed to obtain the hydrodynamic coefficients. The training samples are taken from the free-running model tests of a KVLCC2 ship. Manoeuvring simulation is performed based on the identified hydrodynamic coefficients. Comparisons between the predicted results and experimental results demonstrate the validity of the measures proposed.

The rest of the paper is organized as follows. In Section 2, the reasons for the drift of linear and nonlinear hydrodynamic coefficients are accounted for. In Section 3, three measures are presented to diminish the parameter drift. In Section 4, manoeuvring simulations are performed and comparison results are presented. SVM approach is also described. The final section is conclusion.

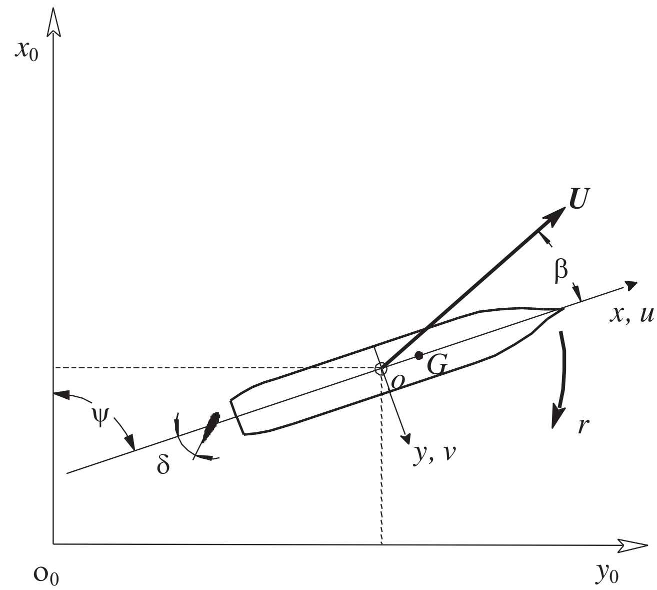

Fig. 1. Coordinate system of ship manoeuvring motion.

2. Parameter drift of hydrodynamic coefficients

When parameter drift happens to hydrodynamic coefficients, the obtained coefficients deviate from their true values. These parameters might be physically incorrect but mathematically correct. This phenomenon can be explained by an example. Using 10°/10° zigzag manoeuvre test data, one can identify the hydrodynamic coefficients in a hydrodynamic model (e.g. Abkowitz model). The obtained manoeuvring model might be able to predict the same manoeuvre (i.e. 10°/10° zigzag manoeuvre) well when manoeuvring simulation is performed. However, for other manoeuvres such as 20°/20° zigzag manoeuvre, the obtained model fails to predict. In a worse case, such a 'mathematically correct' identification even cannot happen.

The reason for the drift of linear hydrodynamic coefficients can be explained from the point of view of mechanics. Hwang [31] and Clarke et al. [38] applied the slender-body theory to calculate the linear force and moment in the ship manoeuvring motion. It was found that dynamic cancellation happened and resulted in the simultaneous drift of linear hydrodynamic coefficients. Different from the linear hydrodynamic coefficients, it is difficult to obtain theoretical calculation for nonlinear hydrodynamic coefficients. As a result, the reason for the drift of nonlinear hydrodynamic coefficients cannot be explained physically. Nevertheless, it can be explained from another point of view, i.e., statistically. By means of regression analysis, it can be concluded that the drift of nonlinear hydrodynamic coefficients results from the so-called multicollinearity.

2.1. Simultaneous drift of linear hydrodynamic coefficients

The motion of a ship can be described in a six-degree-of-freedom frame. In detail, the motion concerns surge, sway, yaw, heave, pitch, and roll. From the point of view of prediction of manoeuvring, attention is often paid to the ship motion in the horizontal plane instead of the vertical plane. In other words, only surge, sway and yaw are taken into account. Fig. 1 depicts the ship manoeuvring motion. The inertial coordinate system is denoted by $x_0o_0y_0$, xoy is the attached coordinate system, G is the center of gravity, u is the surge speed,

v is the sway speed, r is the yaw rate, U is the total velocity, δ is the rudder angle, ψ is the heading angle, and β is the drift angle.

During a ship manoeuvre, the significant hydrodynamic forces are primarily the sway force and yaw moment. According to the slender-body theory, the sway force and yaw moment can be calculated as [26]:

$$Y = -\frac{1}{2}\rho\pi d^2 u_0 \left(v + \frac{1}{2}Lr\right), \quad (1)$$

$$N = -\frac{1}{4}\rho\pi d^2 L u_0 \left(v + \frac{1}{2}Lr\right). \quad (2)$$

where ρ is the fluid density, d the draft of the ship, u_0 the service speed of the ship, L the length of ship. It should be noted that a Coriolis-centripetal term $mu_0 r$ has been involved in the sway force (1). Similarly, an added-moment-of-inertia term $mx_G u_0 r$ has been considered in the yaw moment (2). In terms of hydrodynamic coefficients, the above two expressions can be rewritten as

$$Y = Y_v v + Y_r r, \quad (3)$$

$$N = N_v v + N_r r, \quad (4)$$

where

$$Y_v = -\frac{1}{2}\rho\pi d^2 u_0, \quad (5)$$

$$Y_r = -\frac{1}{4}\rho\pi d^2 u_0 L, \quad (6)$$

$$N_v = -\frac{1}{4}\rho\pi d^2 L u_0, \quad (7)$$

$$N_r = -\frac{1}{8}\rho\pi d^2 L^2 u_0. \quad (8)$$

In steady turning, the pivot point of a ship is located near the bow. It can be inferred that:

$$v + \frac{1}{2}Lr \approx 0. \quad (9)$$

As a result, the approximations hold:

$$Y_v v + Y_r r \approx 0, \quad (10)$$

$$N_v v + N_r r \approx 0, \quad (11)$$

which implies Y_v and Y_r are possible to drift simultaneously, so are N_v and N_r.

In transient motion for instance zigzag manoeuvre, Fig. 2 presents the variation of linear components of sway force and yaw moment during the 10°/10° zigzag manoeuvre of a *Mariner* vessel [39]. It is noted that prime system is adopted to obtain nondimensional variables:

$$v' = \frac{v}{U}, \quad (12)$$

$$r' = \frac{rL}{U}, \quad (13)$$

$$\delta' = \delta. \quad (14)$$

As can be recognized, the following linear approximations hold when the rudder angle is stable:

$$Y'_v v' + Y'_r r' \approx k_1 Y'_\delta \delta', \quad (15)$$

$$N'_v v' + N'_r r' \approx k_2 N'_\delta \delta', \quad (16)$$

$$v' \approx k_3 \delta', \quad (17)$$

$$r' \approx k_4 \delta', \quad (18)$$

where $k_1 \sim k_4$ are constants. Two more approximations can be derived:

$$k_3 Y'_v + k_4 Y'_r \approx k_1 Y'_\delta, \quad (19)$$

Table 1
Correlation coefficients of a linear manoeuvring model.

Coef.	v'	r'	δ'
v'	1.00	0.90	0.31
r'		1.00	0.67
δ'			1.00

$$k_3 N'_v + k_4 N'_r \approx k_2 N'_\delta. \quad (20)$$

The above relationships can be also verified through the calculation of hydrodynamic coefficients. According to the slender-body theory, the rudder force and moment be calculated as:

$$F(\delta) = \frac{1}{2}\rho\pi d^2 u_0^2 \delta, \quad (21)$$

$$M(\delta) = \frac{1}{4}\rho\pi d^2 u_0^2 L\delta. \quad (22)$$

It can be defined that $Y_\delta = \frac{1}{2}\rho\pi d^2 u_0^2$, $N_\delta = \frac{1}{4}\rho\pi d^2 u_0^2 L$. Referring to the definitions of Y_v, Y_r, N_v, N_r and nondimensional operation, the linear dependence in Eqs. (19) and (20) can be confirmed.

As can be recognized from Eqs. (19) and (20), there are many possible combinations for the parameter sets (Y'_v, Y'_r, Y'_δ) and (N'_v, N'_r, N'_δ) to satisfy the linear expressions. In other words, parameter drift might happen.

2.2. Drift of nonlinear hydrodynamic coefficients

Different from the linear hydrodynamic coefficients, it is very difficult to calculate the nonlinear hydrodynamic coefficients theoretically, which makes it impossible to physically explain the drift of hydrodynamic coefficients. Nevertheless, such an effect can be explained by means of regression analysis. Essentially, the purpose of SI application to the ship manoeuvring is to obtain a multiple regression model that reflects the characteristics of ship manoeuvring motion. The hydrodynamic coefficients in the regression model should be determined. However, when two or more explanatory variables in the multiple regression model are highly linearly correlated, the so-called multicollinearity happens. In this situation, it is difficult to obtain accurate coefficient estimates in the multiple regression model since the estimates might vary erratically with the small changes in data. Nevertheless, multicollinearity does most likely not reduce the predictive power of the regression model as a whole even if the coefficients involved might be incorrect.

Multicollinearity is a commonplace in the regression analysis [40]. This phenomenon cannot be eliminated but only alleviated or diminished since for a regression model the input variables are always linearly correlated to each other, more or less. Moreover, this phenomenon is more likely to happen and be serious when the regression model contains a large number of parameters.

Multicollinearity can be detected by several indicators such as F-test, variance inflation factor (VIF) or tolerance (reciprocal of VIF), eigenanalysis, and correlation coefficient. Thereof, the correlation coefficient presents an intuitive and effective indicator. Usually, if the absolute value of a correlation coefficient approximates one, it is indicated that the collinearity is serious. The correlation coefficient between variables x_1 and x_2 can be defined as:

$$\rho_{x_1 x_2} = \frac{\mathrm{cov}(x_1, x_2)}{\sqrt{D(x_1)D(x_2)}}, \quad (23)$$

where $D(x_i)$ denote the variance, $\mathrm{cov}(x_1, x_2)$ the covariance.

Table 1 presents the correlation analysis w.r.t. the explanatory variables v', r', δ', combined with the data that are used to plot Fig. 2, i.e., the 10°/10° zigzag manoeuvre data of the *Mariner* vessel [39].

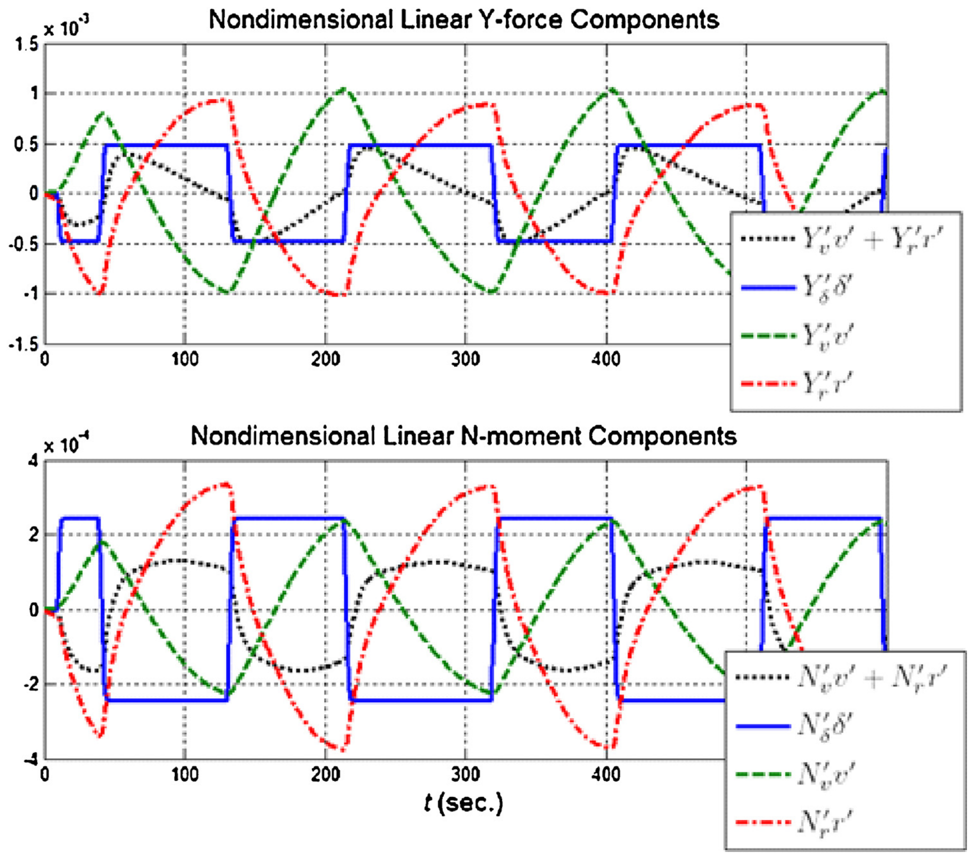

Fig. 2. Nondimensional linear components of sway force and yaw moment for 10°/10° zigzag manoeuvre of a *Mariner* vessel.

As can be recognized, v' and r' is highly linearly correlated. Therefore, the estimates of corresponding hydrodynamic coefficients Y'_v, Y'_r, N'_v, N'_r would deviate from their true values, which has been confirmed in the previous subsection.

3. Measures to diminish the drift of hydrodynamic coefficients

To diminish the drift of hydrodynamic coefficients, some measures have been proposed. For linear hydrodynamic coefficients, the methods of parallel processing, exaggerated over- and underestimation, parameter transformation had been verified [10,31,32]. However, these methods did not work well for nonlinear hydrodynamic coefficients. For nonlinear hydrodynamic coefficients, modification of input scenario was proposed [13,33,34]. However, the applicability of this method is limited because it is required to design particular rudder command. Another approach to deal with the drift of nonlinear hydrodynamic coefficients is to conduct sensitivity analysis [35–37]. However, there are difficulties to determine the criteria of importance and the reference value of hydrodynamic coefficients. Usually, this method is combined with simulation data, similar to the method of modification of scenario. In this paper, combined with experimental data, several measures are proposed to diminish the drift of hydrodynamic coefficients, including linear and nonlinear coefficients. The main purpose of these measures is to alleviate the degree of multicollinearity in the multiple regression model of ship manoeuvring motion.

As aforementioned, multicollinearity is caused by the highly linear correlation between the explanatory variables in a regression model. To alleviate the multicollinearity, an intuitive idea is to modify the explanatory variables, which can be achieved by altering the number of explanatory variables and/or changing the their values. In this paper, three approaches are proposed. First of all, combined with an Abkowitz model, the number of hydrodynamic coefficients in the model is reduced by means of correlation analysis. Then, the samples w.r.t. the explanatory variables in the simplified model are reconstructed by means of difference operation and an additional excitation. The illustration of measures is combined with experimental data. The original samples are taken from the 25°/5° zigzag manoeuvre of a KVLCC2 ship, which was conducted in the Hamburg Ship Model Basin (HSVA).

3.1. Simplification of the manoeuvring model

A general form of Abkowitz model can be described as:

$$\begin{bmatrix} m' - X'_{\dot u} & 0 & 0 \\ 0 & m' - Y'_{\dot v} & m'x'_G - Y'_{\dot r} \\ 0 & m'x'_G - N'_{\dot v} & I'_z - N'_{\dot r} \end{bmatrix} \begin{bmatrix} \Delta \dot u' \\ \Delta \dot v' \\ \Delta \dot r' \end{bmatrix} = \begin{bmatrix} \Delta f'_1 \\ \Delta f'_2 \\ \Delta f'_3 \end{bmatrix}, \tag{24}$$

where $\Delta u'$, $\Delta v'$, $\Delta r'$ are small velocity perturbations from nominal values, $\Delta f'_1$, $\Delta f'_2$, $\Delta f'_3$ are nonlinear functions in which a lot of hydrodynamic coefficients are contained. Take the yaw-equation as an example, there are 22 coefficients in the expression of $\Delta f'_3$ [39]:

$$\begin{aligned} \Delta f_3{}' = {} & N'_{0u}\Delta u' + N'_{0uu}\Delta u'^2 + N'_v\Delta v' + N'_r\Delta r' + N'_\delta\Delta\delta' + N'_{vvv}\Delta v'^3 \\ & + N'_{\delta\delta\delta}\Delta\delta'^3 + N'_{vvr}\Delta v'^2\Delta r' + N'_{vv\delta}\Delta v'^2\Delta\delta' + N'_{v\delta\delta}\Delta v'\Delta\delta'^2 \\ & + N'_{\delta u}\Delta\delta'\Delta u' + N'_{vu}\Delta v'\Delta u' + N'_{ru}\Delta r'\Delta u' + N'_{\delta uu}\Delta\delta'\Delta u'^2 \\ & + N'_{rrr}\Delta r'^3 + N'_{vrr}\Delta v'\Delta r'^2 + N'_{vuu}\Delta v'\Delta u'^2 + N'_{ruu}\Delta r'\Delta u'^2 \\ & + N'_{r\delta\delta}\Delta r'\Delta\delta'^2 + N'_{rr\delta}\Delta r'^2\Delta\delta' + N'_{rv\delta}\Delta r'\Delta v'\Delta\delta' + N'_0. \end{aligned} \tag{25}$$

Table 2
Correlation coefficients of a nonlinear manoeuvring model.

Coef.	v'	r'	$\|v'\|v'$	$\|v'\|r'$	δ'	δ'^3	$v'\delta'^2$	$v'^2\delta'$	$\|r'\|r'$	$v'\|r'\|$	$r'\delta'^2$	$r'^2\delta'$	$r'v'\delta'$
v'	1.00	0.45	0.98	0.67	0.91	0.92	0.99	0.97	0.39	0.84	0.54	0.54	0.68
r'	0.44	1.00	0.42	0.84	0.53	0.54	0.47	0.43	0.97	0.66	0.91	0.75	0.81
$\|v'\|v'$	0.83	0.31	1.00	0.66	0.83	0.85	0.98	1.00	0.32	0.77	0.50	0.42	0.67
$\|v'\|r'$	0.34	0.21	0.38	1.00	0.62	0.64	0.68	0.66	0.75	0.87	0.92	0.73	1.00
δ'	0.64	0.44	0.23	0.01	1.00	0.99	0.91	0.83	0.50	0.83	0.61	0.71	0.62
δ'^3	0.50	0.33	0.25	0.13	0.74	1.00	0.92	0.85	0.50	0.83	0.62	0.69	0.64
$v'\delta'^2$	0.84	0.41	0.77	0.36	0.48	0.66	1.00	0.98	0.40	0.83	0.55	0.53	0.69
$v'^2\delta'$	0.81	0.31	0.99	0.39	0.22	0.29	0.82	1.00	0.33	0.77	0.50	0.42	0.67
$\|r'\|r'$	0.34	0.88	0.03	0.07	0.54	0.35	0.28	0.04	1.00	0.62	0.86	0.81	0.72
$v'\|r'\|$	0.57	0.27	0.21	0.46	0.58	0.41	0.40	0.19	0.30	1.00	0.78	0.82	0.89
$r'\delta'^2$	0.19	0.17	0.08	0.58	0.21	0.29	0.09	0.06	0.05	0.30	1.00	0.83	0.91
$r'^2\delta'$	0.29	0.32	0.15	0.16	0.72	0.44	0.09	0.18	0.49	0.62	0.50	1.00	0.73
$r'v'\delta'$	0.32	0.11	0.33	0.90	0.01	0.09	0.26	0.32	0.16	0.49	0.73	0.24	1.00

Table 3
Condition number of correlation coefficient matrix.

	Condition number
Without difference	3.2×10^5
With difference	2.7×10^3

Table 4
Comparison of correlation coefficients.

Coef.	$r(k)$	$r(k)+y_a(k)$
$v(k)U(k)$	0.465	0.081
$r(k)U(k)$	0.996	0.011
$\|v(k)\|v(k)$	0.450	0.026
$\|v(k)\|r(k)$	0.849	0.002
$\delta(k)U^2(k)$	0.552	0.028
$\delta^3(k)U^2(k)$	0.556	0.022
$v(k)\delta^2(k)U(k)$	0.491	0.005
$v^2(k)\delta(k)$	0.455	0.029
$\|r(k)\|r(k)$	0.023	0.834
$v(k)\|r(k)\|$	0.970	0.039
$r(k)\delta^2(k)U(k)$	0.665	0.015
$r^2(k)\delta(k)$	0.912	0.013
$r(k)v(k)\delta(k)$	0.771	0.024

Table 5
Principal particulars of a KVLCC2 ship.

Description	Full-scale	KVLCC2
Scale ratio	1:1	1:45.714
Perpendicular length (L_{pp})	320.0 m	7 m
Length on water line (L_{wl})	325.5 m	7.1204 m
Breadth (B)	58 m	1.2688 m
Ship depth (D)	30.0 m	0.6563 m
Draft (d)	20.8 m	0.4550 m
Block coefficient (C_B)	0.8098	0.8098
Displacement (∇)	312,622 m^3	3.2724 m^3

Similarly, there are 16 and 22 hydrodynamic coefficients in $\Delta f_1'$ and $\Delta f_2'$ respectively. Namely, 60 hydrodynamic coefficients are contained in the right-hand side of Eq. (24). In fact, some of the nonlinear hydrodynamic coefficients can be removed from so complicated a model. On one hand, those coefficients are difficult to be determined no matter which method is adopted. On the other hand and more importantly, a reduced manoeuvring model maintains predictive power [39]. A complicated manoeuvring model can be simplified by considering the physical meaning of hydrodynamic terms in the model, e.g. [10,29]. Sensitivity analysis provides another way to simplify a complicated manoeuvring model, e.g. [35–37]. In this study, the simplification is performed from the point of view of correlation analysis.

Rewriting the third and twelfth terms on the right-hand side of (25) yields:

$$N_v' \Delta v(k) U(k) + N_{vu}' \Delta v(k) \Delta u(k), \tag{26}$$

where k is the sampling time. It is noted that variables are taken as dimensional forms while the hydrodynamic coefficients are kept as nondimensional forms. This is because when system identification is employed to derive the hydrodynamic coefficients, it is directly combined with experimental data. Since the acceleration is nondimensionalized in $U^2(k)$ while velocity in $U(k)$, a representation as (26) can be obtained. In the case of moderate manoeuvres, the total velocity $U(k)$ can be approximated by:

$$U(k) \approx u_0 + \Delta u(k). \tag{27}$$

Thus, the expression (26) evolves to:

$$N_v' \Delta v(k) u_0 + N_v' \Delta v(k) \Delta u(k) + N_{vu}' \Delta v(k) \Delta u(k). \tag{28}$$

As can be recognized, the second term is linearly correlated to the third one. To reduce the multicollinearity, one of them can be removed from the model. Since the linear derivative N_v' is significant in the manoeuvring model, the nonlinear derivative N_{vu}' is ignored. Likewise, other six nonlinear derivatives, $N_{0uu}', N_{\delta u}', N_{ru}', N_{\delta uu}', N_{vuu}', N_{ruu}'$, in the expression (25) can be ignored. Furthermore, if the effect of surge speed u on the change of yaw moment N is ignored, the term $N_{0u}' \Delta u'$ can be also removed from (25). Thus, the expression (25) is reduced to:

$$\begin{aligned} \Delta f_3' = {} & N_v' \Delta v' + N_r' \Delta r' + N_\delta' \Delta \delta' + N_{vvv}' \Delta v'^3 + N_{vvr}' \Delta v'^2 \Delta r' + N_{rrr}' \Delta r'^3 \\ & + N'_{vrr} \Delta v' \Delta r'^2 + N_{\delta\delta\delta}' \Delta \delta'^3 + N_{vv\delta}' \Delta v'^2 \Delta \delta' + N_{v\delta\delta}' \Delta v' \Delta \delta'^2 \\ & + N_{r\delta\delta}' \Delta r' \Delta \delta'^2 + N_{rr\delta}' \Delta r'^2 \Delta \delta' + N_{rv\delta}' \Delta r' \Delta v' \Delta \delta' + N_0'. \end{aligned} \tag{29}$$

As can be recognized, the number of coefficients has been reduced from 22 to 14. Furthermore, if cross flow models are taken to replace the coupling third-order terms between $\Delta v'$ and $\Delta r'$, one has:

$$\begin{aligned} \Delta f_3' = {} & N_v' \Delta v' + N_r' \Delta r' + N_\delta' \Delta \delta' + N_{|v|v}' |\Delta v'| \Delta v' + N_{|v|r}' |\Delta v'| \Delta r' \\ & + N_{|r|r}' |\Delta r'| \Delta r' + N_{v|r|}' \Delta v' |\Delta r'| + N_{\delta\delta\delta}' \Delta \delta'^3 + N_{vv\delta}' \Delta v'^2 \Delta \delta' \\ & + N_{v\delta\delta}' \Delta v' \Delta \delta'^2 + N_{r\delta\delta}' \Delta r' \Delta \delta'^2 + N_{rr\delta}' \Delta r'^2 \Delta \delta' \\ & + N_{rv\delta}' \Delta r' \Delta v' \Delta \delta' + N_0'. \end{aligned} \tag{30}$$

In the same way, the simplified forms of $\Delta f_1'$ and $\Delta f_2'$ in the model (24) can be obtained:

$$\begin{aligned} \Delta f_1{}' = {} & X_u' \Delta u' + X_{vv}' \Delta v'^2 + X_{rr}' \Delta r'^2 + X_{\delta\delta}' \Delta \delta'^2 \\ & + X_{vr}' \Delta v' \Delta r' + X_{v\delta}' \Delta v' \Delta \delta' + X_{r\delta}' \Delta r' \Delta \delta' + X_0', \end{aligned} \tag{31}$$

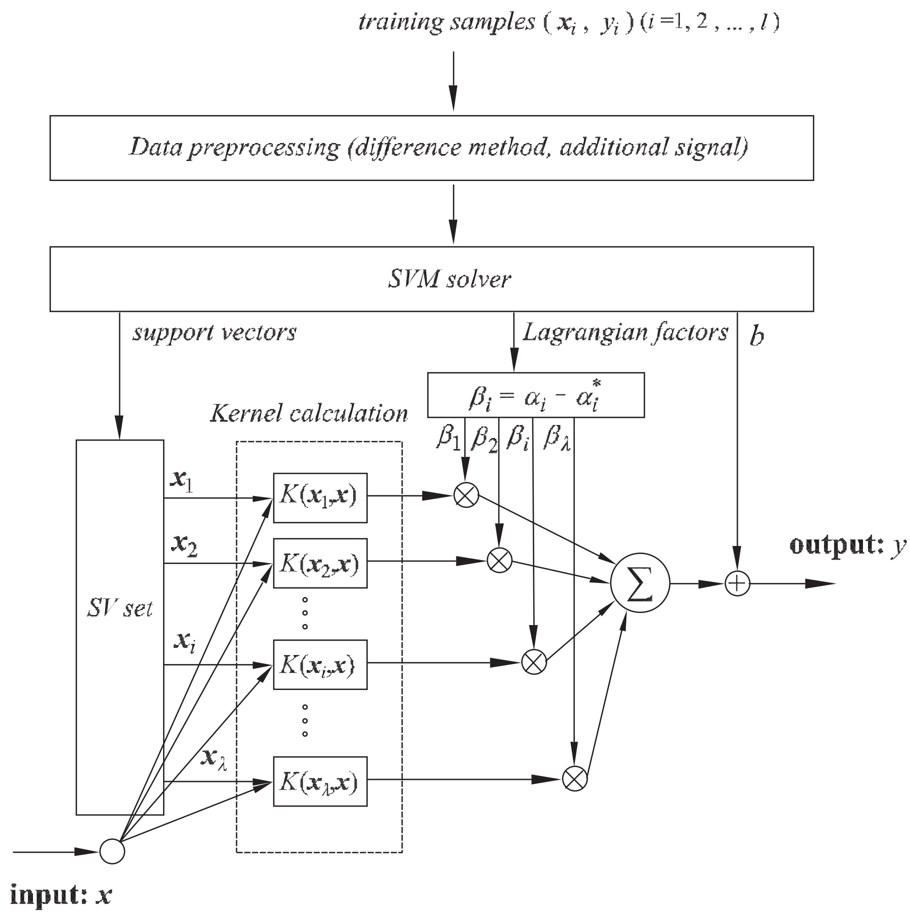

Fig. 3. SVM regression.

Table 6
Nondimensional hydrodynamic coefficients ($\times 10^{-5}$).

Const.	Value	X-Eq.	V1	V2	Y-Eq.	V1	V2	N-Eq.	V1	V2
$X'_{\dot{u}}$	−95.4	X'_u	−93	−42940	Y'_v	−358	−14180	N'_v	−6.3	1250
$Y'_{\dot{v}}$	−1283	X'_{vv}	149	−59740	Y'_r	1980	5202	N'_r	−74	2559
$Y'_{\dot{r}}$	0	X'_{rr}	−108	4220	Y'_δ	448	1998	N'_δ	−165	−287
$N'_{\dot{v}}$	0	$X'_{\delta\delta}$	−105	450	$Y'_{\lvert v\rvert v}$	−3.5	11016	$N'_{\lvert v\rvert v}$	20	−2396
$N'_{\dot{r}}$	−107	X'_{vr}	−237	−1130	$Y'_{\lvert v\rvert r}$	30	10720	$N'_{\lvert v\rvert r}$	−9.9	−336
x'_G	3486	$X'_{v\delta}$	172	2050	$Y'_{\lvert r\rvert r}$	679	−1057	$N'_{\lvert r\rvert r}$	−17	3707
m'	1908	$X'_{r\delta}$	−433	1350	$Y'_{v\lvert r\rvert}$	158	5181	$N'_{v\lvert r\rvert}$	−43	−820
I'_z	119	X'_0	−48	60130	$Y'_{\delta\delta\delta}$	−94	−5377	$N'_{\delta\delta\delta}$	22	155
					$Y'_{v\delta\delta}$	−3.6	43222	$N'_{v\delta\delta}$	17	6266
					$Y'_{vv\delta}$	−7.3	−1558	$N'_{vv\delta}$	12	1661
					$Y'_{r\delta\delta}$	−23	−5108	$N'_{r\delta\delta}$	22	623
					$Y'_{rr\delta}$	134	−1209	$N'_{rr\delta}$	−40	2835
					$Y'_{rv\delta}$	−28	−15214	$N'_{rv\delta}$	3.9	6200
					Y'_0	−6.6	233	N'_0	0.2	−3.3

$$\begin{aligned}\Delta f_2{}' = \; & Y'_v\Delta v' + Y'_r\Delta r' + Y'_\delta\Delta\delta' + Y'_{|v|v}|\Delta v'|\Delta v' + Y'_{|v|r}|\Delta v'|\Delta r' \\ & + Y'_{|r|r}|\Delta r'|\Delta r' + Y'_{v|r|}\Delta v'|\Delta r'| + Y'_{\delta\delta\delta}\Delta\delta'^3 + Y'_{vv\delta}\Delta v'^2\Delta\delta' \\ & + Y'_{v\delta\delta}\Delta v'\Delta\delta'^2 + Y'_{r\delta\delta}\Delta r'\Delta\delta'^2 + Y'_{rr\delta}\Delta r'^2\Delta\delta' \\ & + Y'_{rv\delta}\Delta r'\Delta v'\Delta\delta' + Y'_0.\end{aligned} \tag{32}$$

As can be recognized, the total number of hydrodynamic coefficients in $\Delta f'_1$, $\Delta f'_2$, $\Delta f'_3$ has decreased remarkably, from 60 to 36.

3.2. Difference method

Once the structure of a manoeuvring model is determined, the samples play a supporting role in obtaining a regression model with accurate coefficient estimates since the degree of linear correlation between explanatory variables depends on their sample values. In the study, reconstruction of samples is conducted by means of difference method and an additional excitation.

To illustrate the difference method, a general regression model is given as:

$$y(k) = A^{\mathrm{T}}\mathrm{X}(k) + b, \tag{33}$$

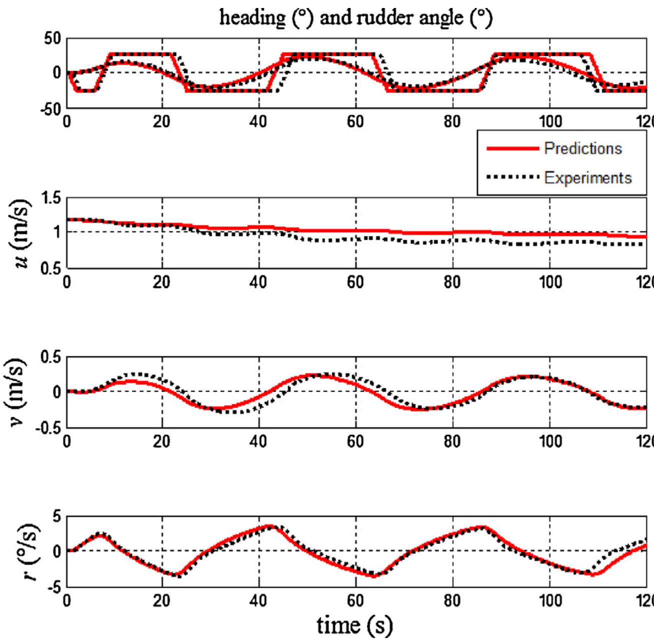

Fig. 4. Prediction of 25°/5° zigzag manoeuvre of a KCLCC2 ship.

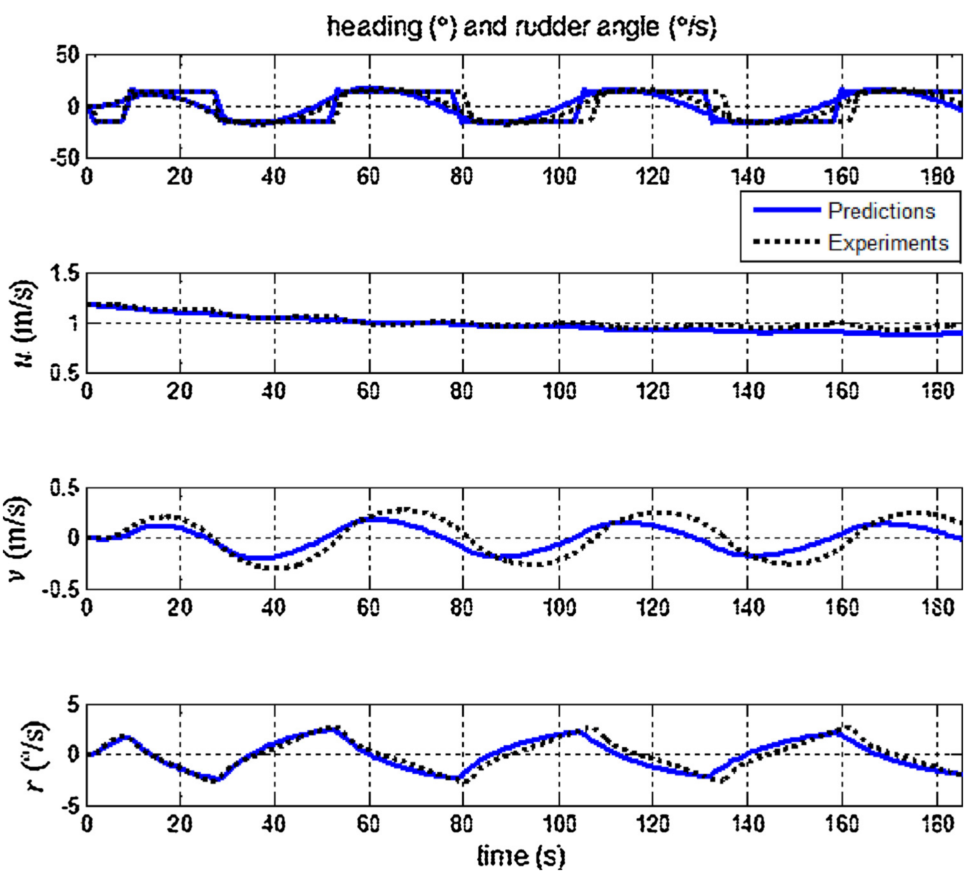

Fig. 5. Prediction of 15°/5° zigzag manoeuvre of a KCLCC2 ship.

where $A = [a_1, a_2, \cdots, a_n]_{n\times1}$ is a coefficient vector, b is a constant, $\mathrm{X}(k) = [x_1(k), x_2(k), \cdots, x_n(k)]_{n\times1}$ is the explanatory variable vector. At a neighbour sampling time, it holds:

$$y(k-1) = A^{\mathrm{T}}\mathrm{X}(k-1) + b. \tag{34}$$

Define:

$$z(k-1) = y(k) - y(k-1), \quad \mathrm{Y}(k-1) = \mathrm{X}(k) - \mathrm{X}(k-1),$$

one has

$$z(k-1) = A^{\mathrm{T}}\mathrm{Y}(k-1). \tag{35}$$

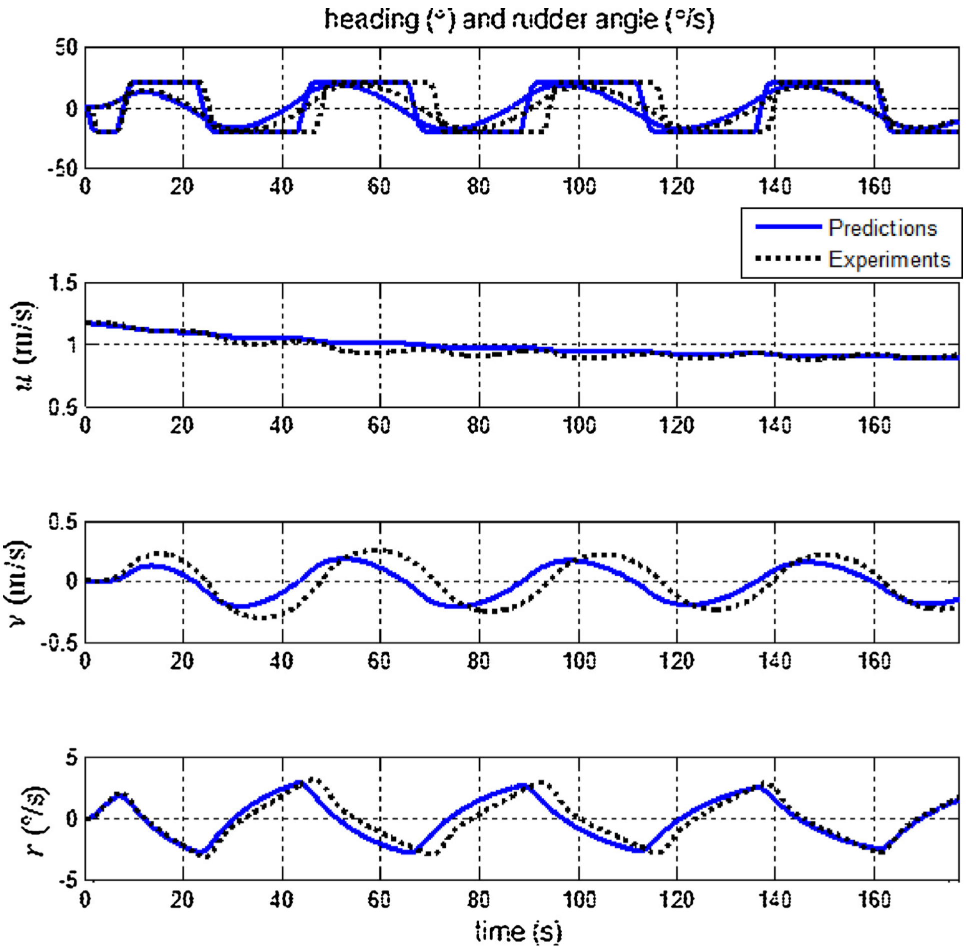

Fig. 6. Prediction of 20°/5° zigzag manoeuvre of a KCLCC2 ship.

As can be recognized from Eqs. (34) and (35), the explanatory variables in two models are different while the coefficient vector remains unchanged. It can be inferred that if the multicollinearity is serious in the original model (34), that situation could be alleviated in the new model (35) after difference of samples. As an example, Table 2 lists the comparison of correlation coefficients between any two explanatory variables in Eq. (30). It should be noted that $\Delta v' = v'$, $\Delta r' = r'$, $\Delta\delta' = \delta'$ hold if the initial state of manoeuvring motion satisfies $v'_0 = r'_0 = \delta'_0 = 0$. As shown in Table 2, the elements below the principal diagonal are the correlation coefficients of samples after difference (i.e. reconstructed samples) while those elements above the principal diagonal are the correlation coefficients of samples without difference (i.e. original samples). The condition numbers of the correlation coefficient matrices are listed in Table 3. As can be recognized, the multicollinearity has been decreased significantly.

3.3. Additional excitation

As can be recognized, the difference method deals with all explanatory variables in a model when reconstructing samples. When the interest is focused on individual explanatory variables, another approach can be used to reconstruct samples, i.e., the method of additional excitation. Take the model (24) as an example, a discrete form of the yaw-equation can be written as:

$$r(k+1) = r(k) + \Theta^{\mathrm{T}}\mathrm{R}(k). \tag{36}$$

where the coefficient vector Θ and the variable vector $\mathrm{R}(k)$ are defined as:

$$\Theta = [\theta_1, \theta_2, \cdots, \theta_{14}]_{14\times1}, \tag{37}$$

$$\begin{aligned}\mathrm{R}(k) = \; & \big[v(k)U(k),\, r(k)U(k),\, \delta(k)U^2(k),\, |v(k)|v(k),\, |v(k)|r(k),\, |r(k)|r(k), \\ & v(k)|r(k)|,\, \delta^3(k)U^2(k),\, v^2(k)\delta(k),\, v(k)\delta^2(k)U(k),\, r(k)\delta^2(k)U(k), \\ & r^2(k)\delta(k),\, r(k)v(k)\delta(k),\, U^2(k)\big]_{14\times1}.\end{aligned} \tag{38}$$

It is noted that coefficients $\theta_1 \sim \theta_{14}$ are determined by hydrodynamic coefficients [24].

In the model (36), explanatory variables are $r(k)$ and $\mathrm{R}(k)$ while the output is $r(k+1)$. To reconstruct samples, a virtual signal can be added to the regression model (36). 'Virtual' means the signal is not obtained from real experiments but by calculation or computer simulation, different from the original samples $\{(r(k), \mathrm{R}(k)) \mapsto r(k+1)\}$ obtained through experiments. A general form of the virtual signal can be written as:

$$y_a(k) = g(x(k)), \tag{39}$$

where $g(\cdot)$ denotes a generalized function. Different representations of $g(\cdot)$ can be used according to specific applications. In the study, the samples for regression analysis is taken from zigzag manoeuvres, which indicates the periodical characteristics of the samples. Therefore, the virtual signal can be designed as a non-periodical signal for instance a ramp signal:

$$y_a(k+1) = y_a(k) + \epsilon, \tag{40}$$

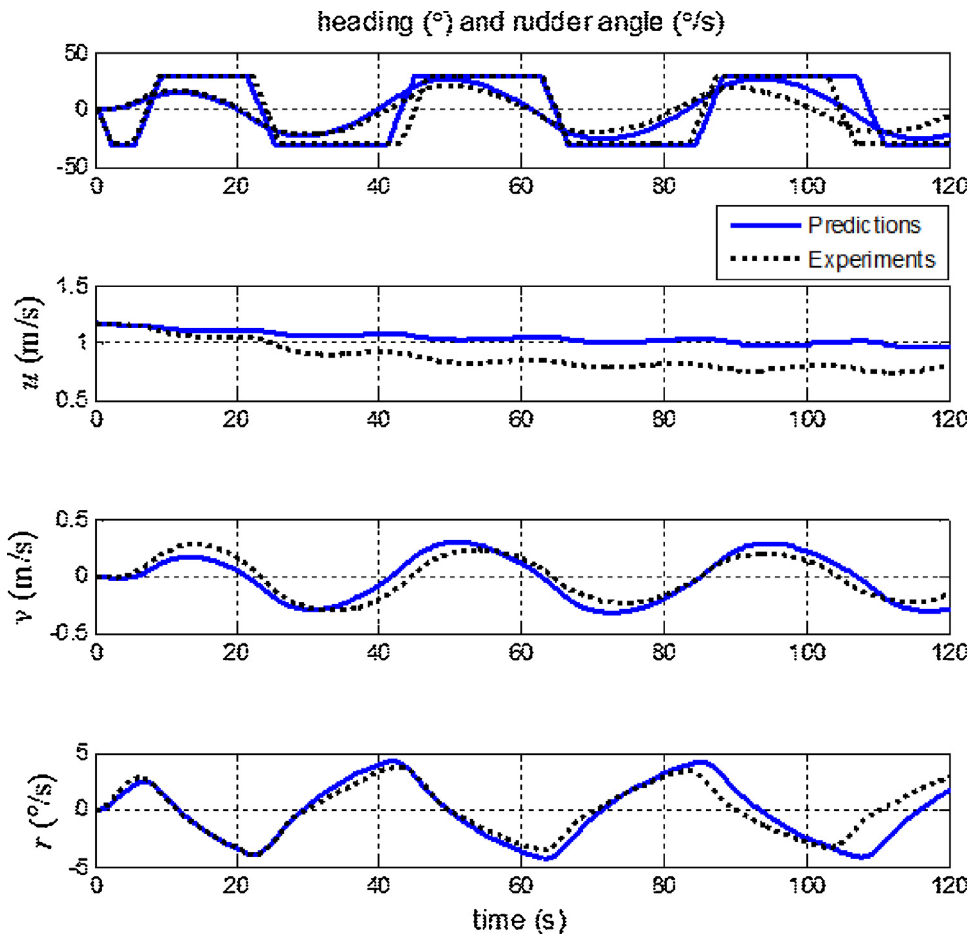

Fig. 7. Prediction of 30°/5° zigzag manoeuvre of a KCLCC2 ship.

where ϵ is a constant. Adding this signal to the model (36) yields a new regression model:

$$[r(k+1)+y_a(k+1)] = [r(k)+y_a(k)] + \Theta^{\mathrm{T}}\mathrm{R}(k)+\epsilon. \tag{41}$$

From the comparison between the models (36) and (41), it can be recognized that the outputs and the first explanatory variables are different in two models, however the coefficient vector Θ keeps unchanged. Since the system output is changed, the added signal (40) can be viewed as an additional excitation to the system (36). From the point of view of regression analysis, the multicollinearity in the regression model could be alleviated due to the new explanatory variable $[r(k)+y_a(k)]$). Assuming $\epsilon = 1$ and the initial value $y_a(0) = 0$, Table 4 lists the comparison of correlation coefficients between the first explanatory variable (i.e. $r(k)$ for system (36) while $r(k)+y_a(k)$ for system (41)) and the other explanatory variables (i.e. elements in the vector $\mathrm{R}(k)$). As can be recognized from the model (41), only the first explanatory variable is changed after the additional signal is incorporated. In other words, the additional excitation takes effect on individual explanatory variables, instead of all explanatory variables.

As can be seen from the comparison, the degree of collinearity decreases remarkably after a signal is attached.

4. Example study

To verify the measures proposed in the study, the hydrodynamic coefficients in the simplified models (30)–(32) are to be determined using SVM based system identification. Samples for identification are preprocessed by difference method and an additional excitation as (40) is incorporated. After the hydrodynamic coefficients are determined, manoeuvring simulation is performed to obtain the predicted results.

4.1. Data samples

Data samples are taken from the free-running model tests of a KVLCC2 ship model, including 15°/5°, 20°/5°, 25°/5°, 30°/5° and 20°/10° zigzag manoeuvres. Thereof, 400 samples from the 25°/5° zigzag manoeuvre test are used for system identification, while all the rest data are used for prediction. The principal particulars of the KVLCC2 ship are listed in Table 5.

4.2. SVM based SI

For given training samples (x_i, y_i), SVM aims to derive a regression model as:

$$y = \sum_{i=1}^{\lambda} \alpha_i \mathrm{K}(x_i, x) + b, \tag{42}$$

where α_i are Lagrangian factors, b is a constant, $\mathrm{K}(x_i, x)$ are kernel functions. To determine α_i and b, convex quadratic programming theory can be used [41]. A simpler scheme is to solve a linear matrix equation [42]:

$$\begin{bmatrix} 0 & \mathbf{e}^{\mathrm{T}} \\ \mathbf{e} & \mathbf{K}+C^{-1}\mathbf{I} \end{bmatrix} \begin{bmatrix} b \\ \boldsymbol{\alpha} \end{bmatrix} = \begin{bmatrix} 0 \\ \mathbf{y} \end{bmatrix}, \tag{43}$$

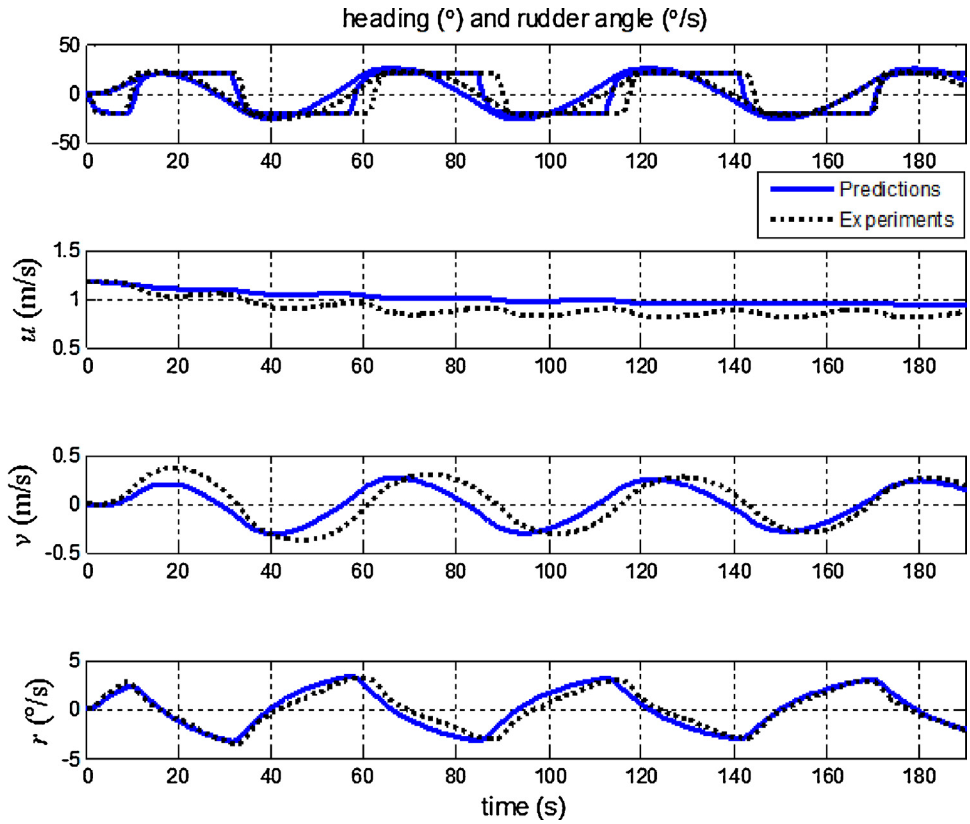

Fig. 8. Prediction of 20°/10° zigzag manoeuvre of a KCLCC2 ship.

where C is the regularization factor, $\mathbf{e} = [1, 1, \cdot, 1]_{l\times 1}$, l is the number of samples, $\mathbf{I}$ is a l-dimensional unit matrix, $\mathbf{K}$ is the l-dimensional kernel matrix with elements $\mathrm{K}(x_i, x_j)$, $\boldsymbol{\alpha} = (\alpha_i)_{l\times 1}$, $\mathbf{y} = (y_i)_{l\times 1}$.

After α_i and b are determined, combined with the known sample data x_i, the regression model (42) can be used to predict a new system output y in response to a new input x. A SVM regression and prediction processes can be depicted as Fig. 3. As can be seen, before SVM regression, samples have been processed using the method of difference and additional excitation.

Different representations of $\mathrm{K}(x_i, x)$ are available for specific applications. For parameter identification, linear kernel function, i.e. $\mathrm{K}(x_i, x) = (x_i \cdot x)$, is preferred. In the study, the hydrodynamic coefficients in the manoeuvring model can be determined directly from the regression results. SVM regression model has the form as:

$$y_i = \left(\sum_{j=1}^{\lambda} \alpha_j x_j \right) \cdot x_i + b, \tag{44}$$

if linear kernel is adopted. Take the yaw-equation (36) as an example, an augmented coefficient vector and an augmented variable vector can be defined as:

$$\Theta' = [1, \theta_1, \theta_2, \cdots, \theta_{14}]_{15\times 1}, \tag{45}$$

$$\begin{aligned} \mathrm{R}'(k) = & \left[r(k), v(k)U(k), r(k)U(k), \delta(k)U^2(k), |v(k)|v(k), |v(k)|r(k), \right. \\ & |r(k)|r(k), v(k)|r(k)|, \delta^3(k)U^2(k), v^2(k)\delta(k), v(k)\delta^2(k)U(k), \\ & \left. r(k)\delta^2(k)U(k), r^2(k)\delta(k), r(k)v(k)\delta(k), U^2(k) \right]_{15\times 1}. \end{aligned} \tag{46}$$

Thus, Eq. (36) can be rewritten as:

$$r(k+1) = \Theta'^{\mathrm{T}} \cdot \mathrm{R}'(k). \tag{47}$$

Comparing (44) with (47), it can be inferred that the coefficient vector Θ' can be estimated by $\left(\sum_{j=1}^{\lambda} \alpha_j x_j \right)$ if the SVM outputs y_i approximate the sample outputs $r(k+1)$ well and the constant b is ignorable.

4.3. Identification results of hydrodynamic coefficients

Table 6 lists the identification results of the hydrodynamic coefficients ('V1' column in the table) and the comparison with the results without sample reconstruction ('V2' column). It is noted that the added masses and added moment of inertia, including $X'_{\dot{u}}$, $Y'_{\dot{v}}$, $Y'_{\dot{r}}$, $N'_{\dot{v}}$, $N'_{\dot{r}}$, are calculated by slender-body theory instead of system identification, due to another parameter identifiability, as stated in Introduction. As can be recognized from the table, the differences between the values in 'V1' column and 'V2' column are significant. An apparently erroneous result happens to the velocity derivative N'_r in 'V2' column. Theoretically, this derivative should be negative.

4.4. Simulation results

Once the hydrodynamic coefficients are obtained, the manoeuvring model (24) is determined and manoeuvring simulation can be performed. Fig. 4 presents the prediction of 25°/5° zigzag manoeuvre and the predicted results are compared with the experimental results. The values in the V1 column in Table 6 are used. Prediction and comparison are also performed with respect to other different zigzag manoeuvres, including 15°/5°, 20°/5°, 30°/5° and 20°/10° zigzag manoeuvres, shown in Figs. 5–8. Predictions of the overshoot angles and the comparison with experimental results are listed in Table 7. As can be seen, prediction results agree well with experimental results, which verifies the proposed methods in the study. Nevertheless, it should be noted that in general, the predictions of

Table 7
Prediction of overshoot angles.

Zigzag manoeuvre	1st overshoot angle			2nd overshoot angle		
	Exp. (°)	Predict (°)	Error (%)	Exp. (°)	Predict (°)	Error (%)
15°/5°	6.64	6.61	0.52	12.8	12.11	5.33
20°/5°	8.05	6.73	16.45	13.85	11.51	16.88
25°/5°	9.94	8.35	16.03	14.99	14.78	1.46
30°/5°	12.17	10.31	15.3	17.1	18.58	8.63
20°/10°	11.71	9.82	16.13	15.62	15.19	2.72

u and v are not as accurate as the perdition of r. It is regarded that the modification of the manoeuvring model needs to be further improved.

5. Conclusions

When system identification is applied to the modeling of ship manoeuvring, parameter drift is an important issue that should be addressed. Whether linear or nonlinear hydrodynamic coefficients, the parameter drift can be regarded resulting from the multi-collinearity in a multiple regression model. To moderate the degree of multicollinearity, modification of the structure of regression model and/or reconstruction of samples can be used. In the study, an Abkowitz model is simplified in which nonlinear terms w.r.t. speed loss are removed. To reconstruct samples, difference method and additional excitation are proposed. It is noted that the proposed reconstruction methods do not require a new manoeuvring test to obtain new samples. Combined with the measures proposed to diminish the parameter drift, SVM is applied to identify the hydrodynamic coefficients in a hydrodynamic manoeuvring model. Manoeuvring simulation is performed based on the regression model. The validity of the proposed measures is verified.

Several problems will be further studied in the next work. The first concern is about the accurate determination of added mass and added moment of inertia due to the limitation of slender-body theory used in the study. Secondly, the modification of manoeuvring model should be developed. Although the number of hydrodynamic coefficients has been decreased, some of nonlinear coefficients seems trivial, in terms of magnitude as can be seen from Table 6. Thirdly, a more effective reconstruction of samples will be studied.

Acknowledgments

This work was partially supported by the Special Item supported by the Fujian Provincial Department of Ocean and Fisheries (No. MHGX-16), and the Special Item for University in Fujian Province supported by the Education Department (No. JK15003). Authors are grateful to the Hamburg Ship Model Basin (HSVA) for providing the experimental data. Authors also appreciate the support from the Collaborative Innovation Center of High-End Equipment Manufacturing in Fujian, China.

References

[1] International Maritime Organization (IMO), Standards for ship manoeuvrability, Resol. MSC 137 (76) (2002).
[2] The Maneuvering Committee of ITTC, Final Report and Recommendations to the 25th ITTC, 25th International Towing Tank Conference, Fukuoka, Japan, 2008, pp. 143–208.
[3] M.A. Abkowitz, Lectures on Ship Hydrodynamics – Steering and Manoeuvrability, Hydro- and Aerodynamics Laboratory, Report No.Hy-5, 1964, Lyngby, Denmark.
[4] A. Ogawa, H. Kasai, On the mathematical model of manoeuvring motion of ships, Int. Shipbuild. Prog. 25 (292) (1978) 306–319.
[5] K. Nomoto, T. Tagushi, K. Honda, S. Hirano, On steering qualities of ships, Int. Shipbuild. Prog. 4 (35) (1957) 354–370.
[6] T. Holzhüter, Robust identification in an adaptive track controller for ships, in: Proceedings of the 3rd IFAC Symposium on Adaptive Systems in Control and Signal Processing, Glasgow, UK, 1989, pp. 275–280.
[7] R. Munoz-Mansilla, J. Aranda, J.M. Diaz, J. de la Cruz, Parameter model identification of high-speed craft dynamics, Ocean Eng. 36 (2009) 1025–1038.
[8] M.N. Hayes, Parameters Identification of Nonlinear Stochastic Systems Applied to Ocean Vehicle Dynamics, Massachusetts Institute of Technology, Cambridge, MA, 1971 (Ph.D. thesis).
[9] J. Van Amerongen, Adaptive steering of ships – a model reference approach, Automatica 20 (1) (1984) 3–14.
[10] M.A. Abkowitz, Measurement of hydrodynamic characteristic from ship maneuvering trials by system identification, Trans. Soc. Naval Arch. Mar. Eng. 88 (1980) 283–318.
[11] L.P. Perera, P. Oliveira, C. Guedes Soares, System identification of nonlinear vessel steering, J. Offsh. Mech. Arct. Eng. 137 (3) (2015) 031302-1–031302-7.
[12] K.J. Astrom, Maximum likelihood and prediction error methods, Automatica 16 (5) (1980) 551–574.
[13] C.G. Kallstrom, K.J. Astrom, Experiences of system identification applied to ship steering, Automatica 17 (1981) 187–198.
[14] W.-W. Zhou, M. Blanke, Identification of a class of nonlinear state-space models using RPE techniques, IEEE Trans. Autom. Control 34 (3) (1989) 312–316.
[15] E.R. Herrero, F. Velasco Gonzalez, Two-step identification of non-linear maneuvering models of marine vessels, Ocean Eng. 53 (2012) 72–82.
[16] R.P. Selvam, S.K. Bhattacharyya, M.R. Haddara, A frequency domain system identification method for linear ship maneuvering, Int. Shipbuild. Prog. 52 (1) (2005) 5–27.
[17] S.K. Bhattacharyya, M.R. Haddara, Parameter identification for nonlinear ship manoeuvring, J. Ship Res. 50 (3) (2006) 197–207.
[18] Y. Chen, Y. Song, M. Chen, Parameters identification for ship motion model based on particle swarm optimization, Kybernetes 39 (6) (2010) 871–880.
[19] Y.T. Dai, L.Q. Liu, S.S. Feng, On the identification of coupled pitch and heave motions using opposition-based particle swarm optimization, Math. Probl. Eng. 2014 (2014) 1–10.
[20] K.-P. Rhee, S.-Y. Lee, Y.-J. Sung, Estimation of manoeuvring coefficients from PMM test by genetic algorithm, in: International Symposium and Workshop on Force Acting on a Manoeuvring Vessel, Val de Reuil, France, 1998.
[21] S. Sutulo, C. Guedes Soares, An algorithm for offline identification of ship manoeuvring mathematical models from free-running tests, Ocean Eng. 79 (2014) 10–25.
[22] M.R. Haddara, Y. Wang, Parametric identification of maneuvering models for ships, Int. Shipbuild. Prog. 46 (445) (1999) 5–27.
[23] W.L. Luo, Z.C. Zhang, Modeling of ship maneuvering motion using neural networks, J. Mar. Sci. Appl. 15 (4) (2016) 426–432.
[24] W.L. Luo, Z.J. Zou, Parametric identification of ship maneuvering models by using support vector machines, J. Ship Res. 53 (1) (2009) 19–30.
[25] W.L. Luo, C. Guedes Soares, Z.J. Zou, Parameter identification of ship maneuvering model based on support vector machines and particle swarm optimization, J. Offsh. Mech. Arct. Eng. 138 (3) (2016) 031101-1–031101-8.
[26] J.N. Newman, Marine Hydrodynamics, M.I.T Press, Cambridge, MA, USA, 1977.
[27] S. Toxopeus, Validation of slender-body method for prediction of linear manoeuvring coefficients using experiments and viscous-flow calculations, in: Proceedings of the Seventh ICHD International Conference on Hydrodynamics, University of Naples Federico II, Ischia, 2006.
[28] T.-I. Lee, K.-S. Ahn, H.-S. Lee, D.-K. Yum, On an empirical prediction of hydrodynamic coefficients for modern ship hulls, in: International Conference on Marine Simulation and Ship Manoeuvrability, MARSIM'03, Kanazawa, Japan, August, 2003.
[29] N.H. Norrbin, Theory and observations on the use of a mathematical model for ship manoeuvring in deep and confined waters, Report No. SSPA-Pub-68. Swedish State Shipbuilding Experimental Tank Goteborg, 1971.
[30] R.C. Zhu, G.P. Miao, J.W. Yu, A computational method for evaluation of added mass and damping of ship based on CFD theory, J. Shanghai Jiao Tong Univ. 43 (2) (2008) 198–203.
[31] W.Y. Hwang, Cancellation effect and parameter identifiability of ship steering dynamics, Int. Shipbuild. Prog. 26 (1982) 90–120.
[32] W.Y. Hwang, Application of System Identification to Ship Maneuvering, Massachusetts Institute of Technology, Cambridge, MA, USA, 1980 (PhD thesis).
[33] H.K. Yoon, K.P. Rhee, Identification of hydrodynamic derivatives in ship maneuvering equations of motion by estimation-before-modeling technique, Ocean Eng. 30 (2003) 2379–2404.
[34] S.M. Yeon, D.J. Yeo, K.P. Rhee, Optimal input design for the identification of low-speed manoeuvring mathematical model, in: International Conference on Marine Simulation and Ship Manoeuvrability (MARSIM'06), Terschelling, Netherlands, June, 2006.
[35] K.P. Rhee, K. Kim, A new sea trial method for estimating hydrodynamic derivatives, Ship Ocean Technol. 3 (3) (1999) 25–44.
[36] M. Viviani, R. Depasale, C.P. Bonvino, et al., Alternative methods for the identification of hydrodynamic derivatives from standard manoeuvres, in: International Conference on Marine Simulation and Ship Manoeuvrability, MARSIM'03, Kanazawa, Japan, August, 2003.
[37] R.R. Shenoi, P. Krishnankutty, R. Panneer Selvam, Sensitivity study of hydrodynamic derivative variations on the maneuverability prediction of a container ship, in: ASME 2015 34th International Conference on Ocean,

Offshore and Arctic Engineering (OMAE2015), American Society of Mechanical Engineers, 2015.
[38] D. Clarke, P. Gedling, G. Hine, Application of manoeuvring criteria in hull design using linear theory, Naval Archit. (1983) 45–68.
[39] M.S. Chislett, J. Strom-Tejsen, Planar motion mechanism tests and full-scale steering and maneuvering predictions for a Mariner class vessel, Int. Shipbuild. Prog. 12 (1965) 201–224.
[40] M.Z. Fabrycy, Multicollinearity caused by specification errors, Appl. Stat. 24 (2) (1975) 250–254.
[41] V.N. Vapnik, Statistical Learning Theory, Wiley, New York, 1998 (Chapter 1).
[42] J.A.K. Suykens, J. De Brabanter, L. Lukas, J. Vandewalle, Weighted least squares support vector machines: robustness and sparse approximation, Neurocomputing 48 (2002) 85–105.