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Identification of Ship Maneuvering Model Using Extended Kalman Filters

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ABSTRACT: Ship maneuvering models are the keys to the research of ship maneuverability, design of ship motion control system and development of ship handling simulators. For various frames of ship maneuvering models, determining the parameters of the models is always a tedious task. System identification theory can be used to establish system mathematical models by the system's input data and output data. In this paper, based on the analysis of ship hydrodynamics, a nonlinear model frame of ship maneuvering is established. System identification theory is employed to estimate the parameters of the model. An algorithm based on the extended Kalman filter theory is proposed to calculate the parameters. In order to gain the system's input and output data, which is necessary for the parameters identification experiment, turning circle tests and Zig-zag tests are performed on shiphandling simulator and the initial data is collected. Based on the Fixed Interval Kalman Smoothing algorithm, a pre-processing algorithm is proposed to process the raw data of the tests. With this algorithm, the errors introduced during the measurement process are eliminated. Parameters identification experiments are designed to estimate the model parameters, and the ship maneuvering model parameters estimation algorithm is extended to modify the parameters being estimated. Then the model parameters and the ship maneuvering model are determined. Simulation validation was carried out to simulate the ship maneuverability. Comparisons have been made to the simulated data and measured data. The results show that the ship maneuvering model determined by our approach can seasonably reflect the actual motion of ship, and the parameter estimation procedure and algorithms are effective.

1 INTRODUCTION

Ship maneuvering models are the keys to the research of ship maneuverability, design of ship motion control system and development of ship handling simulators (Shi et al 2006). For various frames of ship maneuvering models, determining the parameters of the models is always a tedious task. The usual approach to determine the ship model parameters is the ship model test. Ship model test is a reliable and accurate method for this purpose. The test is, however, expensive and time-consuming, and usually dependent on some specific model frame, which limits the application of the valuable data (Li 1999). System identification theory can be used to establish system mathematical models by the system's input data and output data. And it has been effectively used in the fields of space technology (Lacy et al 2005), robotic engineering and underwater engineering (Liu et al 2002). Various methodologies have been employed for system identification tasks, which include neural network (Narendra&Parthasarathy 1990), wavelet analysis (Shi et al 2005), and genetic algorithm (Nyarko&Scitovski 2004). Most of the methodologies prove quite effective with the linear system identification.

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To most applications, the linear ship maneuvering models present limitations because of lack of accuracy. The Kalman filter is an efficient recursive filter that estimates the state of a dynamic system from a series of noisy measurements (Kalman 1960). It is able to provide solutions to what probably are the most fundamental problems in control theory. The extended Kalman filter (EKF) is the nonlinear version of the Kalman filter and is often considered the *de facto* standard in the theory of nonlinear state estimation (Leondes et al 1970). EKF is widely used in areas of state estimation, object tracking and navigation(Beides&Heydt 1991, Farina et al 2002).

Base on EKF and augmented state equation, this paper intended to tackle identification of non-linear ship maneuvering models.

2 EQUATIONS OF SHIP HORIZONTAL MOTION

Two coordinates are set for the description of ship's horizontal motion, as shown in Figure 1. $E-\xi-\eta$ is the space coordinate, and the plane $E\xi\eta$ lies on the water plane. $O-x-y$ is the ship coordinate. Plane Oxy is parallel to $E\xi\eta$. The origin of the coordinate, *O*, is attached on the ship's center of gravity. It is so oriented that *Ox* is aligned with ship's fore and aft line with forward as positive direction, and *Oy* is aligned abeam and with starboard side as positive direction. Let U be ship's velocity, and β be the drift angle.

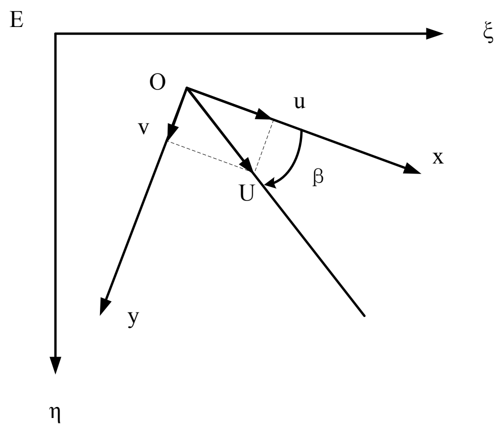

Figure1. Ship's horizontal motion coordinates

Then the motion equations of ship on water surface can be established as,

$$\dot{\boldsymbol{x}}(t) = \boldsymbol{f}(\boldsymbol{x}(t), \boldsymbol{s}(t), t) + \boldsymbol{w}(t)$$
$$\boldsymbol{y}(t) = \boldsymbol{H}\boldsymbol{x}(t) + \boldsymbol{e}(t) \tag{1}$$

where $\boldsymbol{x}(t) = [u(t) \quad v(t) \quad r(t)]^{\mathrm{T}}$, $\boldsymbol{s}(t) = [\delta(t) \quad n(t)]^{\mathrm{T}}$, $\boldsymbol{H} = \boldsymbol{I}_{3\times3}$, $\boldsymbol{f} = [f_1 \quad f_2 \quad f_3]^{\mathrm{T}}$. And u denotes ship's longitudinal velocity, v, the lateral velocity, r, the turning rate of ship's heading, δ, the rudder angle and n, the propeller RPM.

Based on the standard state of the straight motion of ship with constant speed along x axis, the functions f in Equation 1 can be expanded into Taylor series. Compromising the accuracy of the modes and the complexity of the computation of parameter identification, Only are the second and lower order series preserved. Further assumptions are made that the ship is symmetrical with *x* axis and nearly symmetrical with *y* axis, and that the origin of the coordinate of ship motion is on the gravity center of the ship. With these assumptions, some of the partial derivatives in the Taylor series would be zeros and the equations can be further simplified. Because the longitudinal resistance is proportional to u^2, the zero order, the first order and the second order items of u can be combined and represented as $a_1 u(t)^2$ (Li 1999). Then we have,

$$\begin{aligned} f_1 &= a_1 u(t)^2 + a_2 v(t)^2 + a_3 r(t)^2 + a_4 \delta(t)^2 + a_5 v(t) r(t) \\ &\quad + a_6 v(t)\delta(t) + a_7 r(t)\delta(t) + a_8 u(t) n(t) + a_9 n(t)^2 \\ f_2 &= b_1 v(t) + b_2 r(t) + b_3 \delta(t) + b_4 u(t) r(t) \\ f_3 &= c_1 v(t) + c_2 r(t) + c_3 \delta(t) \end{aligned} \tag{2}$$

where $a_i (i = 1,2,\cdots,9)$, $b_i (i = 1,2,3,4)$, $c_i (i = 1,2,3)$ are the parameters of the model. The identification task is to determine these parameters.

3 CALCULATION OF MODEL PARAMETERS USING EKF

In order to identify the parameters, a_i, b_i and c_i, of ship maneuvering model, the extended Kalman filter (EKF) algorithm is employed. The parameters of the model are also taken as the state variables and then the augmented state space contains the model parameters as well as the original state variables. Hence, the augmented state equation can be established. Our algorithm of parameter identification is based on the EKF method and the augmented state equation.

Take the parameters, a_i, b_i and c_i, in Equation 2 as state variables and expand Equation 1, then the augmented state equation and the observation equation are established as,

$$\dot{\boldsymbol{x}}^a(t) = \boldsymbol{f}^a(\boldsymbol{x}^a(t), \boldsymbol{s}(t), t) + \boldsymbol{w}(t)$$
$$\boldsymbol{y}(t) = \boldsymbol{H}\boldsymbol{x}^a(t) + \boldsymbol{e}(t) \tag{3}$$

where

$$\boldsymbol{x}^a(t) = [u(t) \quad v(t) \quad r(t) \quad a_i(t) \quad b_i(t) \quad c_i(t)]^{\mathrm{T}}_{1\times19},$$

$$\boldsymbol{H} = \begin{bmatrix} 1 & 0 & 0 & 0 & \cdots & 0 \\ 0 & 1 & 0 & 0 & \cdots & 0 \\ 0 & 0 & 1 & 0 & \cdots & 0 \end{bmatrix}_{3\times19}$$

Equation 3 can be discretized and transformed into the following discrete non-linear state function,

$$\boldsymbol{x}^a(k+1) = \boldsymbol{f}^a(\boldsymbol{x}^a(k), \boldsymbol{s}_m(k), k) + \boldsymbol{\omega}(k)$$
$$\boldsymbol{y}(k) = \boldsymbol{H}\boldsymbol{x}^a(k) + \boldsymbol{e}(k) \tag{4}$$

Where $\boldsymbol{s}_m(k)$ denotes the average value of sampled values of inputs at $T(k)$ and $T(k+1)$. T is the sampling period. $\boldsymbol{\omega}(k)$ and $\boldsymbol{e}(k)$ are white noise series with variances of $\boldsymbol{Q}$ and $\boldsymbol{R}$, respectively. And, $\boldsymbol{f}^a = \left[f_1^a \quad f_2^a \quad \cdots \quad f_{19}^a \right]^{\mathrm{T}}$.

Where,

$$f_1^a = u(k) + Ta_1(k)u(k)^2 + Ta_2(k)v(k)^2 + Ta_3(k)r(k)^2$$
$$+Ta_4(k)\delta_m(k)^2 + Ta_5(k)v(k)r(k) + Ta_6(k)v(k)\delta_m(k)$$
$$+Ta_7(k)r(k)\delta_m(k) + Ta_8(k)u(k)n_m(k) + Ta_9(k)n_m(k)^2$$
$$f_2^a = v(k) + Tb_1(k)v(k) + Tb_2(k)r(k) + Tb_3(k)\delta_m(k) +$$
$$Tb_4(k)u(k)r(k)$$
$$f_3^a = r(k) + Tc_1(k)v(k) + Tc_2(k)r(k) + Tc_3(k)\delta_m(k)$$
$$f_4^a = a_1(k)$$
$$\vdots$$
$$f_{19}^a = c_3(k)$$

By Equation 4, we have the following EKF recursive equations,

$$\hat{\boldsymbol{x}}^a(k+1|k) = \boldsymbol{f}^a(\hat{\boldsymbol{x}}^a(k), \boldsymbol{s}_m(k), k)$$
$$\boldsymbol{P}(k+1|k) = \boldsymbol{\Phi}\boldsymbol{P}(k)\boldsymbol{\Phi}^{\mathrm{T}} + \boldsymbol{Q}$$
$$\boldsymbol{K}(k+1) = \boldsymbol{P}(k+1|k)\boldsymbol{H}^{\mathrm{T}}[\boldsymbol{H}\boldsymbol{P}(k+1|k)\boldsymbol{H}^{\mathrm{T}} + \boldsymbol{R}]^{-1}$$
$$\boldsymbol{P}(k+1) = [\boldsymbol{I} - \boldsymbol{K}(k+1)\boldsymbol{H}]\boldsymbol{P}(k+1|k)$$
$$\hat{\boldsymbol{x}}^a(k+1) = \hat{\boldsymbol{x}}^a(k+1|k) + \boldsymbol{K}(k+1)[\boldsymbol{y}(k+1) - \boldsymbol{H}\hat{\boldsymbol{x}}^a(k+1|k)] \tag{5}$$

where：

$$\boldsymbol{\Phi} = \left. \frac{\partial \boldsymbol{f}^a}{\partial \boldsymbol{x}^a} \right|_{\boldsymbol{x}^a = \hat{\boldsymbol{x}}^a(k)}$$

By the recursive Equation 5, the filtered vector, $\hat{\boldsymbol{x}}^a(k)$, of the augmented state equation (Equ. 4) can be calculated. Thereby the estimated model parameters, a_i, b_i and c_i, are determined. And hence the ship maneuvering model can be established.

4 IDENTIFICATION PROCEDURES AND VALIDATION ANALYSIS

Shiphandling simulator is used to perform the identification experiment. There are several advantages by using the data retrieved from the shiphandling simulators for the identification purpose. Firstly, simulators can provide the data of ship motion without interference of external factors such as the effect of wind and current. Secondly, accurate ship parameters and maneuvering characteristic are provided. And thirdly, ideal environmental conditions, e.g., uniform water depth, can be set with the operational areas.

4.1 *Data preprocessing*

To get the raw data, Zig-zag test is performed with a shiphandling simulator. The data are recorded with sampling period T=2s. The recorded data are: ship position, s_ξ, s_η, in space coordinate, ship's heading ϕ, rudder angle δ and propeller RPM n. Other data needed, such as ship's longitudinal speed u, lateral speed v, and rate of turn r, can be deduced from the recorded data.

- Let s_ξ be the displacement of ship position on $E\xi$, and u_ξ, a_ξ be the speed and acceleration respectively, which can be calculated using s_ξ. The ship motion along $E\xi$ can be described by the following state equation and observation equation,

$$\boldsymbol{X}(k+1) = \boldsymbol{\Phi}\boldsymbol{X}(k) + \boldsymbol{\omega}(k)$$
$$\boldsymbol{Z}(k) = \boldsymbol{H}(k)\boldsymbol{X}(k) + \boldsymbol{n}(k) \tag{6}$$

where,

$$\boldsymbol{X}(k) = \left[s_\xi(k) \quad u_\xi(k) \quad a_\xi(k) \right]^{\mathrm{T}},$$

$$\boldsymbol{\Phi} = \begin{bmatrix} 1 & T & \frac{T^2}{2} \\ 0 & 1 & T \\ 0 & 0 & 1 \end{bmatrix},$$

$$\boldsymbol{H} = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix},$$

$$\boldsymbol{Z}(k) = \left[s_\xi(k) \right].$$

And $\boldsymbol{\omega}(k)$ is the white noise series with zero mean and variance $\boldsymbol{Q}$,

$$\boldsymbol{Q} = 2\alpha\sigma_a^2 \begin{bmatrix} \frac{1}{20}T^5 & \frac{1}{8}T^4 & \frac{1}{6}T^3 \\ \frac{1}{8}T^4 & \frac{1}{3}T^3 & \frac{1}{2}T^2 \\ \frac{1}{6}T^3 & \frac{1}{2}T^2 & T \end{bmatrix}$$

$\boldsymbol{n}(k)$ is the white noise series with zero mean and variance σ_R^2, a_ξ is the acceleration of the ship motion along $E\xi$, and σ_a^2 is its variance. α is the operation parameter and T is the sampling period (T=2s). By Equation 6, we have the following recursive equations of Kalman filter.

$$\hat{\boldsymbol{X}}(k+1|k) = \boldsymbol{\Phi}\hat{\boldsymbol{X}}(k)$$
$$\boldsymbol{P}(k+1|k) = \boldsymbol{\Phi}\boldsymbol{P}(k)\boldsymbol{\Phi}^{\mathrm{T}} + \boldsymbol{Q}(k)$$
$$\boldsymbol{K}(k+1) = \boldsymbol{P}(k+1|k)\boldsymbol{H}^{\mathrm{T}}[\boldsymbol{H}\boldsymbol{P}(k+1|k)\boldsymbol{H}^{\mathrm{T}} + \sigma_R^2\boldsymbol{I}]^{-1}$$
$$\boldsymbol{P}(k+1) = [\boldsymbol{I} - \boldsymbol{K}(k+1)\boldsymbol{H}]\boldsymbol{P}(k+1|k)$$
$$\hat{\boldsymbol{X}}(k+1) = \hat{\boldsymbol{X}}(k+1|k) + \boldsymbol{K}(k+1)[\boldsymbol{Z}(k+1) - \boldsymbol{H}\hat{\boldsymbol{X}}(k+1|k)] \tag{7}$$

and the smoothing equations for fixed intervals,

$$\hat{\boldsymbol{x}}(k \mid N) = \hat{\boldsymbol{x}}(k) + \boldsymbol{A}_s(k)[\hat{\boldsymbol{x}}(k+1 \mid N) - \boldsymbol{\Phi}\hat{\boldsymbol{x}}(k)]$$
$$\boldsymbol{A}_s(k) = \boldsymbol{P}(k)\boldsymbol{\Phi}^{\mathrm{T}}\boldsymbol{P}^{-1}(k+1 \mid k) \tag{8}$$

The initial conditions for the recursive Kalman filter are,

$$\hat{\boldsymbol{X}}(2) = \begin{bmatrix} Z(2) & \frac{Z(2)-Z(1)}{T} & 0 \end{bmatrix},$$

$$\boldsymbol{P}(2) = \begin{bmatrix} \sigma_R^2 & \frac{\sigma_R^2}{T} & 0 \\ \frac{\sigma_R^2}{T} & \frac{2\sigma_R^2}{T^2} & 0 \\ 0 & 0 & 0 \end{bmatrix},$$

And the initial condition for fixed interval smoothing is,

$$\hat{\boldsymbol{X}}(N \mid N) = \hat{\boldsymbol{X}}(N)$$

By the optimal smoothed vector $\hat{\boldsymbol{x}}(k \mid N)$, the ship's velocity along the $E\xi$ axis, u_ξ, can be calculated.

With similar approaches, the ship's velocity u_η along the $E\eta$ axis can be calculated from the displacement, s_η, on the $E\eta$ axis. The rate of turn, r, can be calculated using ship's heading, ϕ.

The ship's motion speed is,

$$U = \sqrt{u_\xi{}^2 + u_\eta{}^2},$$

And the course made good is,

$$\varphi = \arctan(\frac{u_\xi}{u_\eta}).$$

And then ship's longitudinal and lateral velocities are,

$$u = \cos\beta,$$
$$v = \sin\beta. \tag{9}$$

where β is the drifting angle, $\beta = \varphi - \phi$.

By the preprocessing of the raw data of ship maneuvering tests, we get the smoothed data, δ, n, u, v and r, which can be used for model parameter identification. Figures 2 and 3 illustrate the rate of turn calculated from the raw data and the smooth result, respectively.

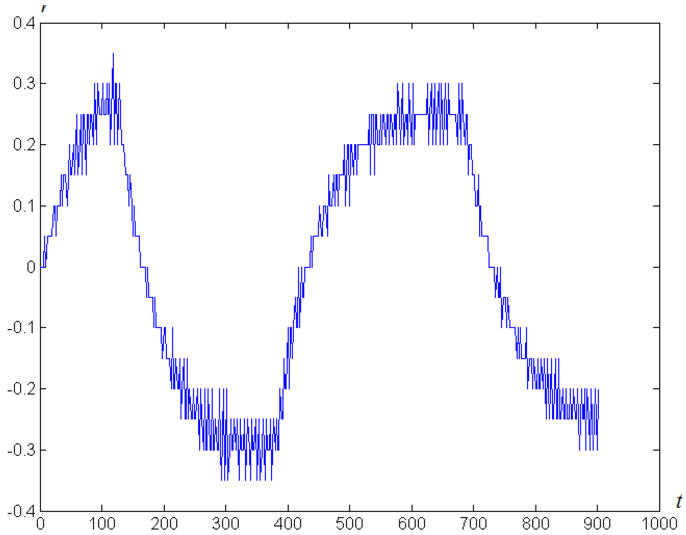

Figure 2. Rate of turn calculated from raw data.

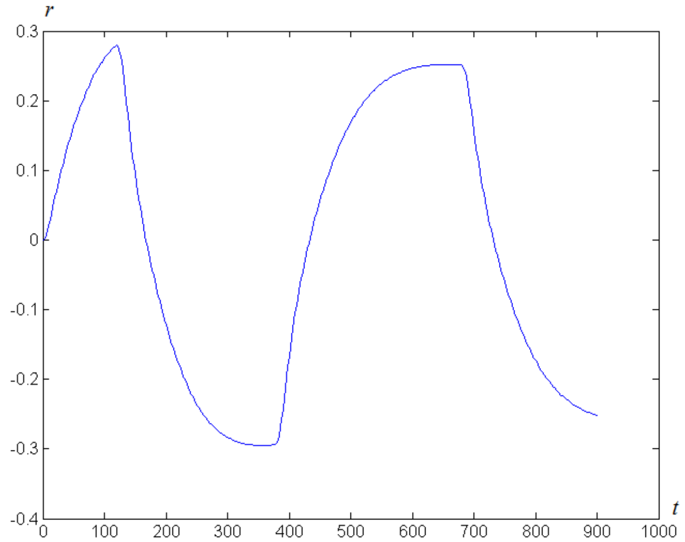

Figure 3. Smoothed rate of turn.

4.2 *Parameter identification*

With the augmented state space, the model parameters in the discrete state equation, Equation 4, are identified. In our experiment, the initial conditions for recursive Equation 5 are set as,

$\boldsymbol{P}(0) = \alpha \boldsymbol{I}$, where $\alpha = 10^5$ and $\boldsymbol{I}$, 19×19 identical matrix

$$\hat{\boldsymbol{x}}^a(0) = \begin{bmatrix} u(0) & v(0) & r(0) & 0 & \cdots & 0 \end{bmatrix}^{\mathrm{T}}$$

Table 1 shows the result of the identification.

Table 1. Result of parameter identification

Param	Value	Param	Value
a_1	1.4347×10^{-4}	a_2	-5.4857×10^{-1}
a_3	-5.0703×10^{-2}	a_4	-7.8174×10^{-6}
a_5	-2.4131×10^{-1}	a_6	2.0968×10^{-4}
a_7	1.7521×10^{-4}	a_8	-3.8163×10^{-5}
a_9	3.8536×10^{-6}	b_1	-1.7511×10^{-1}
b_2	3.3215×10^{-2}	b_3	-2.1508×10^{-4}
b_4	-3.125×10^{-2}	c_1	-1.8988×10^{-2}
c_2	-2.2555×10^{-2}	c_3	1.9627×10^{-4}

4.3 *Convergence and verification of the parameters*

In the experiment, the parameters converged quite well after 200 recursive steps. The convergence status of some of the parameters are shown in Figures 4-6.

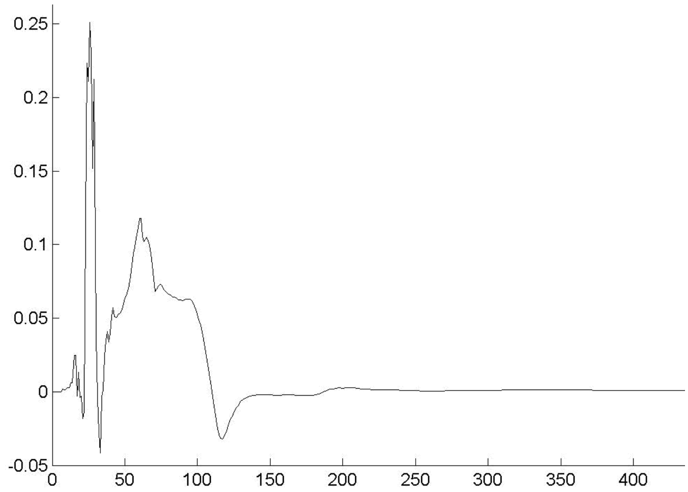

Figure 4. Convergence of the parameters a_1

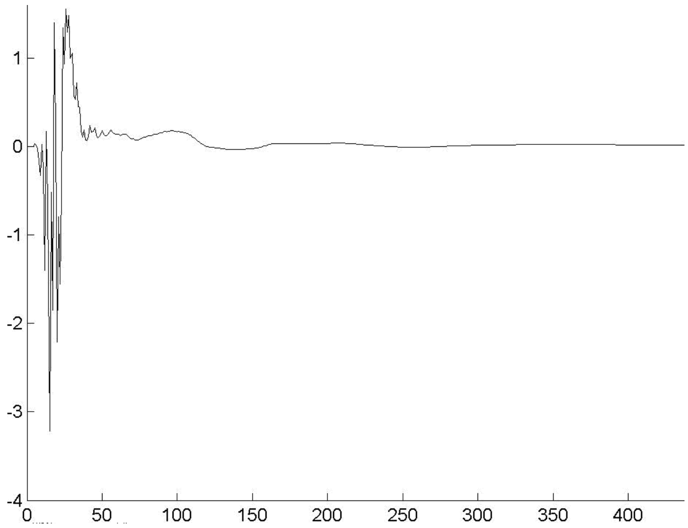

Figure 5. Convergence of the parameters b_2

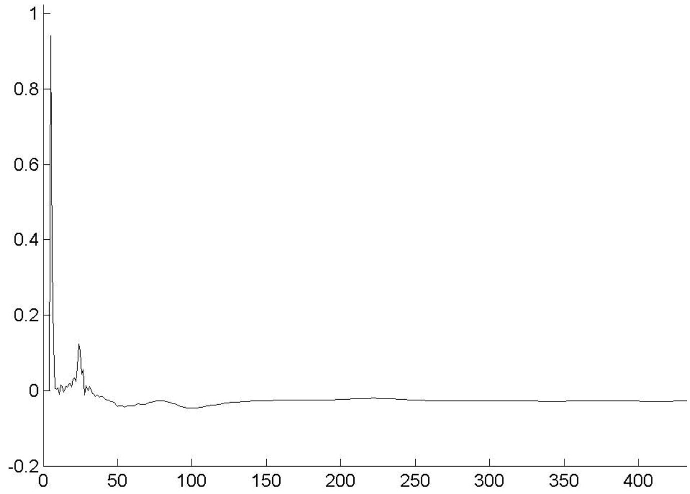

Figure 6. Convergence of the parameters c_1

Using the identified parameters, a_i, b_i, c_i, the non-linear maneuvering model of the target ship can be established. We verify the identified model by performing standard maneuvering tests such as turning circle test, spiral test, zig-zag test, etc., and compare the results. Figure 3 shows the comparison of the ship's headings of zig-zag tests of the identified model and the target ship. Figure 3 is the speed comparison. The comparison of the turning circle tests is illustrated in Figure 4, together with the errors of its elements listed in Table 2. From these results it can be seen that the model output agrees quite well with that of the target ship. Simulation tests show that the ship maneuvering model established by our approach can represent the ship maneuvering with reasonable accuracy.

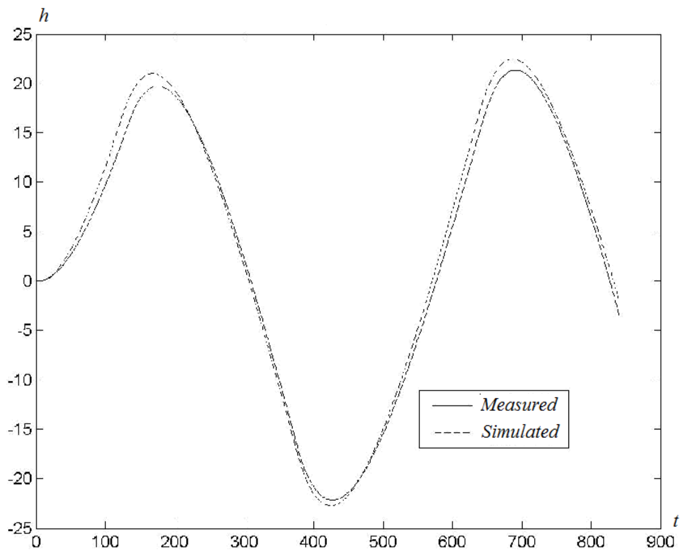

Figure 7. Heading comparison in 20/20 Zig-zag test

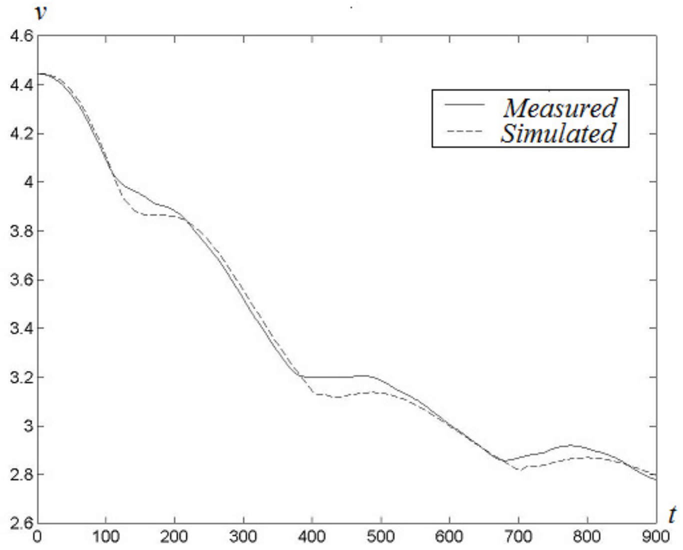

Figure 8. Speed comparison in 20/20 Zig-zag test

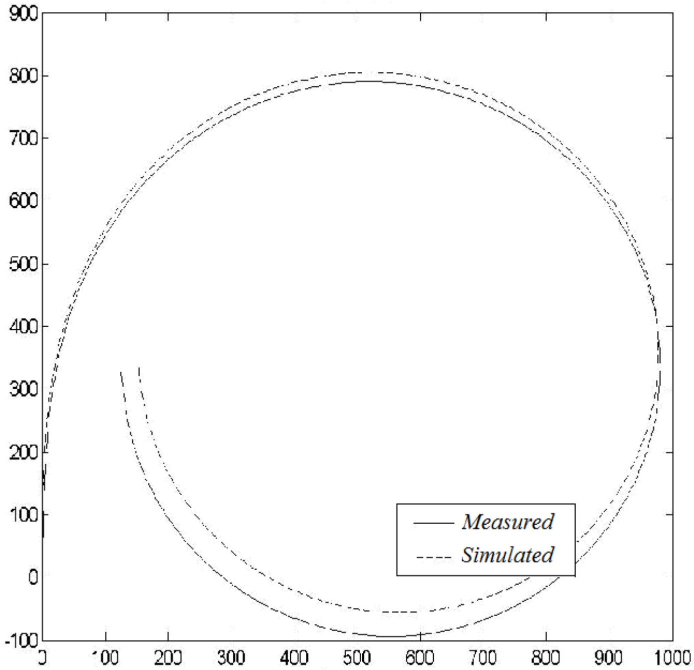

Figure 9. Turning circle comparison

Table 2. Errors with turning circle test.

Items	Measured	Simulated	Error(%)
Advance	790.0	805.0	1.90
Transfer	500.0	525.0	5.00
Diameter	980.0	978.0	-0.20

5 CONCLUSIONS

Based on the analysis of ship hydrodynamics, a nonlinear model frame of ship maneuvering is established. System identification theory is employed to estimate the parameters of the model. An algorithm based on the extended Kalman filter theory is proposed to calculate the parameters. In order to get data samples for the parameters identification experiment, turning circle tests and Zig-zag tests are performed on shiphandling simulator and the raw data is collected. Based on the Fixed Interval Kalman Smoothing algorithm, a pre-processing algorithm is proposed to process the raw data of the tests. With this algorithm, the errors introduced during the measurement process are eliminated. Parameters identification experiments are designed to estimate the model parameters, and the ship maneuvering model parameters estimation algorithm is extended to modify the parameters being estimated. Then the model parameters and the ship maneuvering model are determined. Simulation validation was carried out to simulate the ship maneuverability. Comparisons have been made to the simulated data and measured data. The results show that the ship maneuvering model determined by our approach can reasonably reflect the actual motion of ships, and the parameter estimation procedure and algorithms are effective.

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