System Identification of AUV Hydrodynamic Model Based on Support Vector Machine

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***Abstract*—Autonomous Underwater Vehicle (AUV) has already been applied to ocean resource observation, environmental discovery, underwater rescue and many other types of oceanic activities. To achieve better performance and maneuvering, thus to meet more complex task, the researchers and operators should open new avenues for deeper understanding of AUV dynamics, and on the basis of which, to design more efficient control algorithm. This paper applied support vector machine method, which is derived from machine learning technology, to AUV dynamic parameter identification, and verified the feasibility through simulations.**

***Keywords*—System identification, Sensitivity analysis, Support vector machine, SMO algorithm**

I. Introduction

Traditional identification method for dynamic parameters of underwater vehicles include theoretical analysis, numerical method and restrained model experiment [1]. However, the above methods can not reflect the unstable maneuver of AUV. Moreover, the hydrodynamic characteristics of AUV are not accurately revealed since complex spatial motion is not described. By remotely and automatically controlling, the experimental data obtained from unlimited navigation is able to realize more accurate hydrodynamic parameter identification. As a result, it is of great importance for designing superior controllers based on known maneuverability.

As one of the important modelling method, system identification method [2] has developed rapidly in last decades and has become a major branch of modern control theory. Identification methods that are commonly used include least squares, extended Kalman filter (EFK) and neural network method. These methods' training principle is to minimize experience risk, which often leads to over-fitting, and the numerical abnormality of training process. In addition, the network performance demand large quantity of the sample data, real-time performance is hard to achieve, which all make on-line identification inaccessible.

Using traditional system identification methods, Hayes conducted hydrodynamic parameters identification modeling of Abkowitz model [3] by model reference method (MRM) based on site experimental data of navigation. Van Amerongen [4] established motion identification model of ship by model reference adaptive (MRA) method after both ship and ship model test were conducted.

Based on artificial intelligence technology, artificial neural network overcomes the inherent flaw of the traditional system identification method, and thus is an improved way of system identification [5]. Wang [6] identified the hydrodynamic parameters of maneuver models for underwater vehicles and ships in two ways: neural networks method and frequency-domain spectral analysis method, both through simulation experiments. Zou [7] established ship maneuver model based on neural networks identification, in which the, field test of ship has proven the accuracy of modelling.

Support vector machines (SVM) is a new artificial intelligence method, which emerged in recent years in the field of system identification [8]. Comparing to traditional artificial neural network algorithm, SVM method transform the proposed identification problem into a quadratic optimization problem, which avoids local extreme phenomenon that inevitably brought with neural network method, by obtaining theoretically global optimal point. At the meantime, this method has strong generalization ability, and not requires large quantity of sample data. Therefore, SVM method is more accessible for implementation, it dimension explosion is also able to be avoided [9]. First time proposed by Vapnik in the 1990s, the SVM method has been successfully applied in various aspects such as pattern recognition, regression estimation and probability estimation [10]. Apart from engineering, SVM is widely applied in the financial, which made it a new research direction of artificial intelligence after artificial neural network method. In recent years, the application of SVM has expanded to underwater research field, but only limited in fault diagnosis, economic demonstration and probability prediction. One cannot find many applications for ship hydrodynamics study [11]. Based on phase space reconstruction theory, Sun [12] conducted modelling and forecasting for pitch motion. Luo [13] built the steering model using SVM.

This paper applies SVM method to parameter identification of AUV dynamics model concluded by sensitivity analysis. By the aim of simulation platform, AUV conducted several maneuvers such as one-way navigation on surface, and rotation at constant depth, using the known standard AUV model. The identification model with full parameters is the derivation on

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the basis of standard model simulation result. Comparisons are made to testify model data and sample data.

II. Parameter Identification Modelling

Define the coordinates in Fig.1, the symbolic definition is illustrated in table.1.

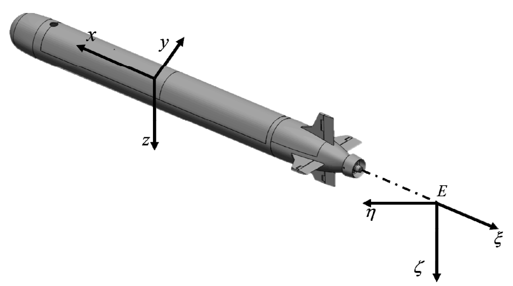


Fig. 1. Fixed Coordinate and Kinematic Coordinate System

A. Sensitivity Model

The Hargen-Gertler 6 DOF hydrodynamic model contains 108 parameters. To simplify the model for identification, Harbin Engineering University studied of the above 108 coefficients [14], and first selected 31 coefficients of zero-value sensitivity, to form zero-value sensitivity model. The simulation results obtained by this model presented consistency at some extend with former model. For the rest of coefficients, change-value sensitivity is calculated to modify zero-value sensitivity model by adding 7 more coefficients, and as a result enhance the consistency. Several tests have already been conducted to demonstrate sufficient accuracy of model, thus applying this sensitivity model will reduce calculation.

TABLE 1. The notation of SNAME (1950) for marine vessels

DOF	Forces and moments	Linear and angular velocities	Positions and Euler angles
1 surge	X	u	x
2 sway	Y	v	y
3 heave	Z	w	z
4 roll, heel	K	p	ϕ
5 pitch, trim	M	q	θ
6 yaw	N	r	ψ

To realize parameter identification more easily, surge velocity is assumed to be constant for test requirement, thus the equation on surge direction is not considered. Transform the sensitivity model to state space model as follow:

$$\begin{bmatrix} m-Y_{\dot v} & 0 & -Y_{\dot p} & 0 & -Y_{\dot r} \\ 0 & m-Z_{\dot w} & 0 & -Z_{\dot p} & 0 \\ -K_{\dot v} & 0 & I_x & 0 & 0 \\ 0 & -M_{\dot w} & 0 & I_y-M_{\dot q} & 0 \\ -N_{\dot v} & 0 & 0 & 0 & I_y-N_{\dot r} \end{bmatrix}\begin{bmatrix}\dot v\\ \dot w\\ \dot p\\ \dot q\\ \dot r\end{bmatrix}=\begin{bmatrix}f_1\\ f_2\\ f_3\\ f_4\\ f_5\end{bmatrix} \quad (1)$$

Where:

$$f_1 = Y_{r|r|}r|r| + Y_r ur + Y_{wp}wp + Y_{\delta_r}u^2\delta_r + Y_{v|r|}\frac{v}{|v|}\left|\left(w^2+v^2\right)^{\frac{1}{2}}\right||r| + Y_v uv + Y_{v|v|}v\left|\left(w^2+v^2\right)^{\frac{1}{2}}\right| - mur + mwp \quad (2)$$

$$f_2 = Z_q uq + Z_{uu}u^2 + Z_w uw + Z_{w|w|}w\left|\left(w^2+v^2\right)^{\frac{1}{2}}\right| + Z_{vv}v^2 + Z_{\delta_s}u\delta_s + Z_{\delta_b}u^2\delta_b + muq - mvp \quad (3)$$

$$f_3 = K_r ur + K_v uv - mhg\cos\theta\sin\phi - \left(I_z - I_y\right)qr \quad (4)$$

$$f_4 = M_q uq + M_{q|w|}\left|\left(w^2+v^2\right)\right|q + M_{uu}u^2 + M_w uw + M_{vv}v^2 + M_{\delta_s}u^2\delta_s + M_{\delta_b}u^2\delta_b - mgh\sin\theta - \left(I_x - I_z\right)rp \quad (5)$$

$$f_5 = N_{r|r|}r|r| + N_r ur + N_{|v|r}\left|\left(w^2+v^2\right)\right|r + N_v uv + N_{\delta_r}u^2\delta_r - \left(I_y - I_x\right)pq \quad (6)$$

B. Identification Model

To simplify identification process, inertial hydrodynamic coefficients are not involved in parameter identification [16]. Aiming at viscous hydrodynamic coefficient, take velocity corresponds to each hydrodynamic coefficients in the state space equation as model identification input, and the acceleration as the output, discretized and non-dimensionalized the differential terms in the output parameters to conclude following equations:

$$
\begin{aligned}
Y(k)*C_Y^{'} &= \left(m^{'}\frac{v(k+1)-v(k)}{LhU^2(k)} - Y_{\dot{r}}^{'}\frac{r(k+1)-r(k)}{hU^2(k)} - Y_{\dot{p}}\frac{p(k+1)-p(k)}{hU^2(k)} + m^{'}\frac{u(k)r(k)}{LU^2(k)} - m^{'}\frac{w(k)p(k)}{LU^2(k)} \right) \\
Z(k)*C_Z^{'} &= \left(\left(m^{'} - Z_{\dot{w}}^{'}\right)\frac{w(k+1)-w(k)}{LhU^2(k)} - Z_{\dot{q}}^{'}\frac{r(k+1)-r(k)}{hU^2(k)} - m^{'}\frac{v(k)p(k)}{LU^2(k)} - m^{'}\frac{u(k)q(k)}{LU^2(k)} \right) \\
K(k)*C_K^{'} &= \left(I_x^{'}\frac{p(k+1)-p(k)}{hU^2(k)} - K_{\dot{v}}^{'}\frac{v(k+1)-v(k)}{LhU^2(k)} + \left(I_z^{'} - I_y^{'}\right)\frac{q(k)r(k)}{U^2(k)} + mgh\cos\theta\sin\phi \right) \\
M(k)*C_M^{'} &= \left(\left(I_y^{'} - M_{\dot{q}}^{'}\right)\frac{q(k+1)-q(k)}{hU^2(k)} - M_{\dot{w}}^{'}\frac{w(k+1)-w(k)}{LhU^2(k)} + \left(I_x^{'} - I_z^{'}\right)\frac{p(k)r(k)}{U^2(k)} + mgh\sin\theta \right) \\
N(k)*C_N^{'} &= \left(\left(I_z^{'} - N_{\dot{r}}^{'}\right)\frac{r(k+1)-r(k)}{hU^2(k)} - N_{\dot{v}}^{'}\frac{v(k+1)-v(k)}{LhU^2(k)} + \left(I_y^{'} - I_x^{'}\right)\frac{p(k)q(k)}{U^2(k)} \right)
\end{aligned}
\tag{7}
$$

Where:

$$
\begin{cases}
Y = \left[r|r|, ur, wp, \dfrac{v}{|v|}\left|\left(w^2+v^2\right)^{\frac{1}{2}}\right||r|, uv, v\left|\left(w^2+v^2\right)^{\frac{1}{2}}\right|, u\delta_r \right]_{1\times7} \\
Z = \left[uq, u^2, uw, w\left|\left(w^2+v^2\right)^{\frac{1}{2}}\right|, v^2, u^2\delta_s, u^2\delta_b \right]_{1\times7} \\
K = \left[ur, uv \right]_{1\times2} \\
M = \left[uq, \left|\left(w^2+v^2\right)^{\frac{1}{2}}\right| q, u^2, uw, v^2, u^2\delta_s, u^2\delta_b \right]_{1\times7} \\
N = \left[r|r|, ur, \left|\left(w^2+v^2\right)^{\frac{1}{2}}\right| r, uv, u^2\delta_r \right]_{1\times7}
\end{cases}
\tag{8}
$$

$$
\begin{cases}
C_Y^{'} = \left[Y_{r|r|}^{'}, Y_r^{'}, Y_{wp}^{'}, Y_{v|r|}^{'}, Y_v^{'}, Y_{v|v|}^{'}, Y_{\delta_r}^{'} \right]_{1\times7}^T \\
C_Z^{'} = \left[Z_q^{'}, Z_{uu}^{'}, Z_w^{'}, Z_{w|w|}^{'}, Z_{vv}^{'}, Z_{\delta_s}^{'}, Z_{\delta_b}^{'} \right]_{1\times7}^T \\
C_K^{'} = \left[K_r^{'}, K_v^{'} \right]_{1\times2}^T \\
C_M^{'} = \left[M_q^{'}, M_{q|w|}^{'}, M_{uu}^{'}, M_w^{'}, M_{vv}^{'}, M_{\delta_s}^{'}, M_{\delta_b}^{'} \right]_{1\times7}^T \\
C_N^{'} = \left[N_{r|r|}^{'}, N_r^{'}, N_{r|v|}^{'}, N_v^{'}, N_{\delta_r}^{'} \right]_{1\times7}^T
\end{cases}
\tag{9}
$$

The above equations are the complete form of parameter identification model, where $\left[Y(k), Z(k), K(k), M(k), N(k)\right]$ is the input vector, $\left[C_Y^{'}, C_Z^{'}, C_K^{'}, C_M^{'}, C_N^{'}\right]$ is the vector of parameters to be identified.

III. PARAMETER IDENTIFICATION BASED ON SUPPORT VECTOR MACHINE

Support vector machine is a supervised learning method, which is widely used in statistical classification and regression analysis. SVM is essentially a two-class classification model [65] which fundamentally defined as the linear interval classifier with the largest interval in the state space. Since the learning strategy of SVM is to maximize interval, it finally transforms into finding solution of convex quadratic programming problem.

A. Mathematical Model of SVM

Knowing that the training sample is in the set $\{(x_i, y_i), \ldots (x_n, y_n)\}$, to sensitivity model, $x_i \in R^9, y_i \in R$. For the above sample data, fitting under the precision of ε, and transform, parameter identification problem is transformed into a convex quadratic programming problem by the support vector machine method, presented in eq.10

$$
\begin{aligned}
\max L(\alpha,\beta) = \max -\frac{1}{2}\sum_{i,j=1}^{n}(\alpha_i-\beta_i)(\alpha_j-\beta_j)k(x_i,x_j) - \varepsilon\sum_{i=1}^{n}(\alpha_i+\beta_i) \\
+ \sum_{i=1}^{n} y_i(\alpha_i-\beta_i)
\end{aligned}
\tag{10}
$$

$$
s.t. \begin{cases}
\alpha_i, \beta_i \ge 0, i = 1, 2, \ldots n \\
\sum_{i=1}^{n}\alpha_i - \sum_{i=1}^{n}\beta_i = 0
\end{cases}
$$

Where: $\max L(\alpha,\beta)$ is the item to be optimized, α,β is the Lagrange multiplier, $k(x_i, x_j)$ is the Kernel function, in this paper of form $k(x_i, x_j) = \langle x_i, x_j \rangle$.

The most efficient solution of the above problem is by applying Sequential Minimal Optimization (SMO) method by calculating the value of α,β, the value of ω is easily deduced from $\omega=\sum_{i=1}^{n} x_i(\alpha_i-\beta_i)$. Since $\omega=\left[C'_Y, C'_Z, C'_K, C'_M, C'_N\right]$, the hydrodynamic coefficients are identified.

IV. SIMULATION TEST

The simulations of field test of AUV is run on the basis of a standard AUV hydrodynamic model with known coefficients. These results used as reference to test the identified model accuracy.

A.Parameter Identification Result

First set velocity as 6 knot, use 20°Z-type steering data as sample data for support vector machine method model parameters identification. The identification process is shown in Fig. 2, and part of identified results shown in Table 2 below.

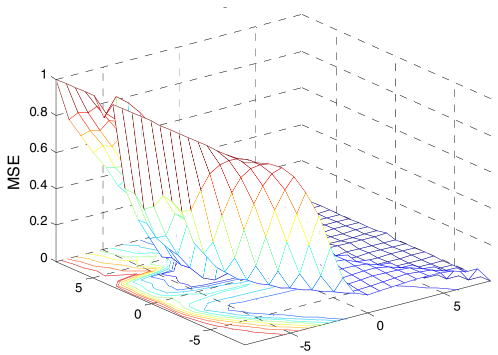


Fig. 2. Parameter Identification Process

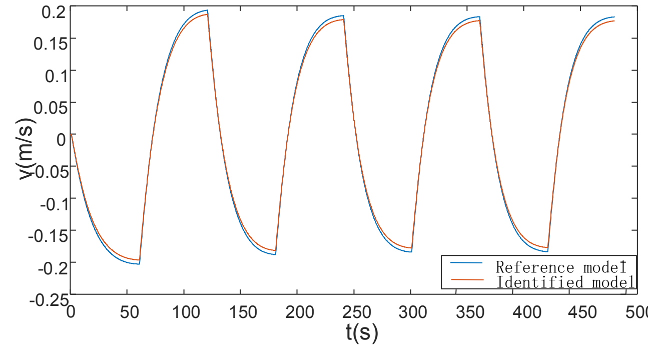
TABLE 2. Parameter Identification Result

Lateral hydrodynamic coefficient	Reference value	Identified value
Y'_v	-725.0	-749.9
$Y'_{v\|v\|}$	-5801.5	-4546.6
$Y'_{v\|r\|}$	-1192.7	-1202.3
Y'_r	118.2	116.3
$Y'_{r\|r\|}$	-409.4	192.6
Y'_{δ_r}	248.1	222.4

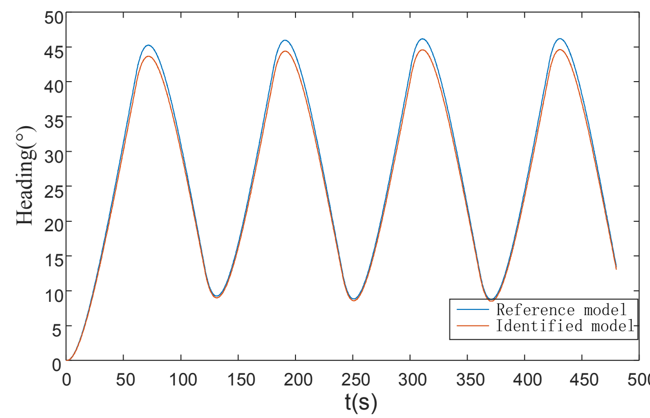
From the data above, the parameter identification results are basically consistent with the standard model. However, it can be easily spotted that significant deviation exists on some parameters. That is because the identification model has simplified coefficients. The large deviation compensates for the ignored hydrodynamic term.

B.Simulation results

First setting the surge velocity for 6 knot, 10°Z-type steering test is run in Matlab simulation platform using both reference model with known coefficients, and identified model using SVM method. Simulation results are shown separately in Fig.3.



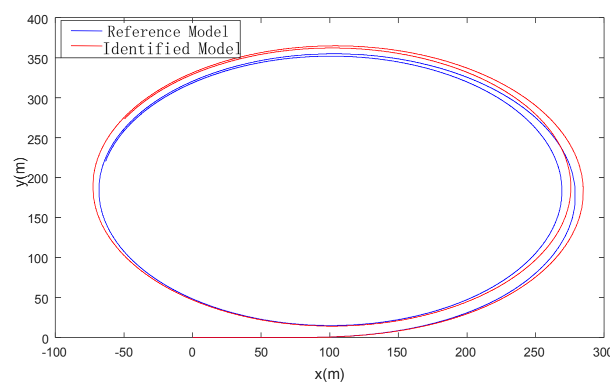
a) Lateral Velocity



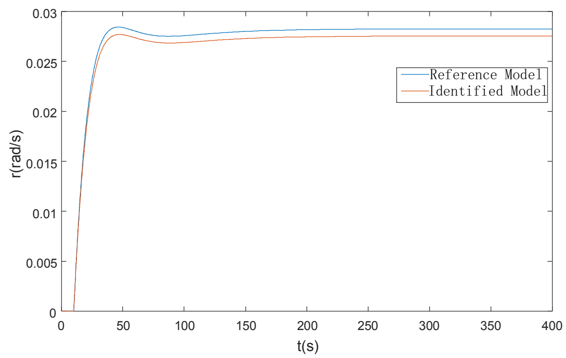
b) Heading

Fig. 3. 10°Z-Type Steering Test Results Comparison

Keep the surge velocity as 6 knot, increase the steering angle from10° to 25°, Z-type simulation test results using both reference model and identified model are shown separately in Fig.4.



a) Trajectory of AUV



b) Heading velocity

Fig. 4. 25° Rotary Steering Test Results Comparison

The above simulation results demonstrate that using the proposed support vector machine method, the prediction model by parameter identification is of satisfactory accuracy based on SVM, without any noise or disturbance concerned.

V. CONCLUSION

This paper selects sensitivity hydrodynamic model for parameter identification. By conducting Z-steering test, and applied SMO algorithm for regression, parameter identification is implemented through support vector machine method. Simulations proved the identified model is consistent with reference model, and thus the proposed identification method is of confidence.

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