Modular Modeling of Autonomous Underwater Vehicle

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***Abstract*—The kernel problem of modular dynamic modeling of autonomous underwater vehicle (AUV) which is the modularization of the hydrodynamic coefficients of the hull is studied in this paper. The hydrodynamic coefficients of the hull are transformed from the lift axis system into the normal-force axis system, where they satisfy the superposition property and can be estimated from the parameters of modular sections. The standard reference model method is proposed for the modularization of these hydrodynamic coefficients. Three different parameterized Myring hulls are used to verify the proposed standard reference model method.**

Keywords-AUV; modular; modeling

I. Introduction

Modular design methods are widely used in the development of autonomous underwater vehicles (AUV), in the sense that the vehicle has a highly reconfigurable modular construction, which allows for a simple integration of different payloads (swapping or adding sensors, e.g.) and independent subsystem development [1]. Modularity of the system in the overall design can not only reduce the size and weight of the vehicle but also diminish the necessary mission support equipments, and at the same time minimize the development and operational costs. Furthermore, the modularity of the system allows the integration of other thrusters to provide full control of the lateral motions. Therefore, the method to construct the dynamic models for these modular designed AUVs needs to be flexible for reconfiguration.

A modular designed AUV usually consists of a nose section, one or more mid-bodies, and a tail section [1-3]. For an AUV that can be reconfigured with modular sections, rebuilding the dynamic model requires lot of effort and time consuming. This is mainly due to the fact that some hydrodynamic parameters can only be obtained accurately through field testing and parameter identification. It is highly desirable not to repeat all the field tests and parameter identification processes again for each newly reconfigured AUV. The objective of this work is to establish a 'parameter list' for each modular section which is determined by either predictive or test-based methods, then the dynamic model of any reconfigured AUV can be constructed readily and precisely by computing the related parameter lists together and transforming these parameters into its body-fixed frame. In this paper we will focus on the kernel problem for rebuilding the dynamic model of a modular designed AUV from modular section parameters.

II. Concept of Modular Modeling

The general six degrees of freedom dynamic equations of an AUV can be expressed in a compact form [4] as

$$M_{RB}\dot{\upsilon} + C_{RB}(\upsilon)\upsilon = \tau_{RB} \tag{1}$$

where M_{RB} is the rigid-body inertia matrix, C_{RB} is the Coriolis and centripetal matrix, and υ is the linear and angular velocity vector in the body-fixed frame. τ_{RB} is a generalized vector of external forces (forces and moments) acting on the AUV, which is composed of three terms as the following equation [4]

$$\tau_{RB} = \tau_R + \tau_E + \tau \tag{2}$$

where τ_R denotes the radiation-induced forces, τ_E denotes the environmental forces acting on the vehicle due to ocean currents and waves, and τ denotes the thruster forces. The environmental forces can be divided into Froude-Kriloff force and diffraction force, which make up the total non-viscous forces acting on a floating body in incident regular waves [5]. The Froude-Kriloff force is the force introduced by the unsteady pressure field generated by undisturbed waves. The diffraction force is due to the floating body disturbing the waves. The environmental forces are mainly related to floating objects. For AUVs operated underwater the environmental forces can be neglected or can be treated as disturbance if needed. The thruster forces are the inputs to the AUV, and can be treated separately. The radiation-induced forces are composed of the restoring forces (weight and buoyancy), and the hydrodynamic forces which include the added mass and the hydrodynamic damping forces as follows

$$\tau_R = \underbrace{-g(\eta)}_{\text{restoring forces}} \underbrace{-M_A\dot{\upsilon} - C_A(\upsilon)\upsilon}_{\text{added mass}} \underbrace{-D(\upsilon)\upsilon}_{\text{damping}} \tag{3}$$

where η is the position and orientation vector in the earth-fixed frame, M_A is the added inertia matrix and $C_A(\upsilon)$ is the matrix of hydrodynamic Coriolis and centripetal. Then the problem of modular modeling can be broken down into three sub-tasks: the modularization of inertial property of the AUV, the modularization of the restoring forces, and the modularization of the hydrodynamic characteristics.

The inertial properties of the AUV which include the mass, the moment of inertia and the location of the center of gravity (CG) with respect to the center of buoyancy (CB) can be calculated directly from the inertial properties of each modular section. The moment of inertia and the location of the CG which depend on the mass distribution are readily available through standard mechanical CAD software. The restoring forces are due to the gravity and buoyancy of the AUV, which can be calculated from the gravity and buoyancy of the modular sections with coordinates transformations. The AUV hydrodynamic characteristics include the added mass and the hydrodynamic damping. The added mass of an AUV reconfigured with modular sections can be calculated with empirical methods [6], if and only if the geometric parameters of the whole vehicle are known, which requires the geometric information of each modular section is included in its parameter list. The damping forces which are quantified as hydrodynamic coefficients are mainly produced from the control fins and the hull. The control fins are usually streamlined, and their hydrodynamic coefficients can be empirically calculated [7] or experimentally tested easily and separately. By ignoring the interference between the fins and the hull, the hydrodynamic damping due to these fins can be calculated readily. Consequently the problem of modular modeling is focused on the modularization of the hydrodynamic coefficients of the hull. It is important to notice that some of the hydrodynamic coefficients of the hull with non-streamlined appendages can only be obtained accurately with test based methods. This is the key problem for modular modeling and will be discussed in this paper.

III. Hydrodynamic Coefficients in Normal Force Axis System

Usually the hydrodynamic damping forces of the hull are calculated in the lift axis system [7], shown in Fig. 1, with the hydrodynamic coefficients in a simplified form as follows

$$\begin{aligned} C_m &= C_{m_\alpha}\alpha + \frac{q}{V_\infty}C_{m_q} \\ C_L &= C_{L_\alpha}\alpha + \frac{q}{V_\infty}C_{L_q} \\ C_D &= C_{D_0} + C_{L_\alpha}\alpha^2 \end{aligned} \quad (4)$$

where C_m, C_L and C_D are the moment, lift and drag coefficients respectively. V_∞ is the free-stream velocity, q is the pitching velocity and α is the angle of attack. C_{m_α}, C_{m_q}, C_{L_α} and C_{L_q} are the coefficients associated with the pitch velocity and the angle of attack. C_{D_0} is the zero-lift drag coefficient.

The hydrodynamic coefficients of the hull in the lift axis system do not satisfy the superposition property, which implies that it is impossible to calculate these coefficients directly from the parameters of the modular sections directly. So the hydrodynamic coefficients are transformed from the lift axis system into the normal-force axis system, where they can be estimated from the parameters of modular sections by the DATCOM method which will be discussed in next subsection.

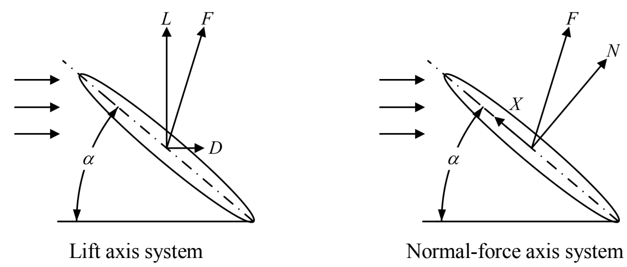

Figure 1. Lift axis system and normal-force axis system

The equations relating the lift and drag coefficients to the normal and chord force coefficients are as follows [7].

$$\begin{cases} C_N = C_L\cos\alpha + C_D\sin\alpha \\ C_X = -C_D\cos\alpha + C_L\sin\alpha \end{cases}, \begin{cases} C_L = C_N\cos\alpha + C_X\sin\alpha \\ C_D = C_N\sin\alpha - C_X\cos\alpha \end{cases} \quad (5)$$

where C_N and C_X are the normal and chord force coefficients respectively. For small attack angle $\cos\alpha \approx 1, \sin\alpha \approx \alpha$, then substitute (4) into (5) we will have the following approximate equations.

$$\begin{cases} C_N \approx C_L + C_D\alpha \approx \left(C_{L_\alpha} + C_{D_0}\right)\alpha + \frac{q}{U_0}C_{L_q} \\ C_X \approx -C_D + C_L\alpha \approx -C_{D_0} \end{cases}$$

If we set $C_{N_\alpha} = C_{L_\alpha} + C_{D_0}$ and $C_{N_q} = C_{L_q}$ the hydrodynamic coefficients in normal-force axis system will be as follows.

$$\begin{aligned} C_m &= C_{m_\alpha}\alpha + \frac{q}{V_\infty}C_{m_q} \\ C_N &= C_{N_\alpha}\alpha + \frac{q}{V_\infty}C_{N_q} \\ C_X &= -C_{D_0} \end{aligned} \quad (6)$$

Then the hydrodynamic damping of the hull can be calculated in the lift axis system with $C_{m_\alpha}, C_{m_q}, C_{N_\alpha}, C_{N_q}$ and C_{D_0} as parameters, or equally in the normal-force axis system with $C_{m_\alpha}, C_{m_q}, C_{L_\alpha}, C_{L_q}$ and C_{D_0} as parameters.

IV. Modularization of the Hydrodynamic Coefficients of the Hull

The DATCOM method summarizes the results of Newtonian impact theory presented in [10] to calculate the aerodynamic characteristics of an arbitrary body of revolution. The DATCOM method is intended to design missiles very often formed by joining two or more cone frustums end to end, which is structurally similar to modular designed AUVs. The purpose of our present work is to adopt the DATCOM method to determine the hydrodynamic coefficients of the hulls reconfigured from modular sections in the normal-force axis system for angle of attack approaching to zero.

A. Modularization of the Normal Force Coefficients

The DATCOM method for estimating the normal force curve slope of the body of revolution is about dividing the body into *m* segments, and summing the normal force curve slope of each segment together to get the whole normal force curve slope of the body [7].

$$C_{N_\alpha} = \sum_{n=1}^{m} \left(C_{N_\alpha}\right)_n \tag{7}$$

The normal force pitching derivative has the same property.

$$C_{N_q} = \sum_{n=1}^{m} \left(C_{N_q}\right)_n \tag{8}$$

B. Modularization of the Moment Coefficients

The DATCOM method for estimating the moment curve slope of the body of revolution is similar to the process of estimating the normal force curve slope, except the influence of the normal force from the each segment [7] as

$$C_{m_\alpha} = \sum_{n=1}^{m} \left(C_{m_\alpha}\right)_n + \sum_{n=1}^{m} \frac{l_n}{d_B} \left(C_{N_\alpha}\right)_n \tag{9}$$

where d_B is the maximum body diameter, and l_n is the distance from the front face of a given segment to the desired moment reference axis of the configuration, positive aft. The moment pitching derivative has similar property.

$$C_{m_q} = \sum_{n=1}^{m} \left(C_{m_q}\right)_n + \sum_{n=1}^{m} -l_n \left(C_{m_\alpha}\right)_n \tag{10}$$

C. Modularization of the Drag Coefficient

The DATCOM method for estimating the zero-lift drag coefficient is by adding the pressure-drag coefficient of each segment to the skin-friction drag coefficient of the body [7] as

$$C_{D_0} = C_{D_f} + \sum_{n=1}^{m} \left(C_{D_p}\right)_n \tag{11}$$

where C_{D_p} is the pressure-drag coefficient for individual segment. The skin-friction drag coefficient can be estimated by

$$C_{D_f} = 1.02 C_f \frac{S_S}{S_B} \tag{12}$$

where C_f is the turbulent friction coefficient as a function of the Reynolds number based on the length of the body, S_B is the maximum section area, and S_S is the wetted area or surface area of the body excluding the base area.

V. STANDARD REFERENCE MODEL METHOD

The modular hydrodynamic coefficients of each individual hull section can be obtained by wind-tunnel or tow-tank model tests which need complicated laboratory testing facilities. We want to calculate the modular hydrodynamic coefficients from the modular equations assuming the hydrodynamic coefficients of the whole hull are known. By ignoring the distance related terms in the moment coefficients, and assuming the skin-friction drag coefficient can be calculated directly and separately, the modular equations in the normal-force axis system are simplified as follows.

$$\begin{aligned} C_{N_\alpha} &= \sum_{n=1}^{m} \left(C_{N_\alpha}\right)_n, C_{N_q} = \sum_{n=1}^{m} \left(C_{N_p}\right)_n \\ C_{m_\alpha} &= \sum_{n=1}^{m} \left(C_{m_\alpha}\right)_n, C_{m_q} = \sum_{n=1}^{m} \left(C_{m_p}\right)_n \\ C_{D_p} &= \sum_{n=1}^{m} \left(C_{D_p}\right)_n \end{aligned} \tag{13}$$

For these equations are all approximation equations, several direct calculation methods have been tried, and we concluded that it is impossible to obtain the values of the modular coefficients from their summations. The standard reference model method is proposed to make the modularization of these hydrodynamic coefficients practical, which means choosing a standard configuration of the modular designed AUV with its hydrodynamic coefficients known, and all the modular sections of the standard configuration are treated as reference modular sections. Any other modular section will be substituted into this standard reference model accordingly, and the differences between the modular hydrodynamic coefficients of the new modular section and that of the reference modular section will be calculated and recorded. Then the hydrodynamic coefficients of hull of any AUV configured with these modular sections can be estimated. In this section we will adopt the most widely used Myring hull to elaborate and verify the proposed standard reference model method.

A. Modular Sections of Myring Hull

The Myring hull is the most widely used hull shape of streamlined AUVs, for its profile describes a body contour with minimal drag coefficient for a given fineness ratio (body length/maximum diameter)[8, 9]. The Myring hull constitutes of a nose-section, a constant-radius center-section and a tail-section with length of *a*, *b*, *c* respectively (see Fig. 2). The Myring hull shape is axis symmetric and the specific section profile is described by the equations of radius distribution along the main axis with the origin set at the front nose point of the hull as follows.

Nose section: $r(x) = \frac{1}{2} d \left[1 - \left(\frac{x-a}{a} \right)^2 \right]^{\frac{1}{n}}$

Middle section: $r(x) = d$

Tail section:

$$r(x) = \frac{1}{2} d - \left[\frac{3d}{2c^2} - \frac{\tan\theta}{c} \right](x-a-b)^2 + \left[\frac{d}{c^3} - \frac{\tan\theta}{c^2} \right](x-a-b)^3$$

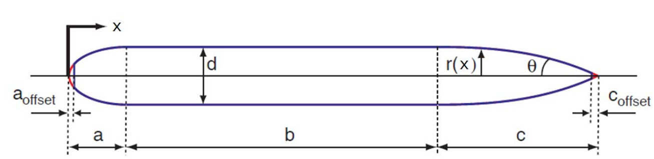

Figure 2. Myring hull profile

TABLE I. MODULAR SECTION GEOMETRIC PARAMETERS

Module Index		1	2	3	Units
Module A	a	0.191	0.248	0.135	m
	a_{offset}	0.0165	0.0165	0.0165	m
	n	2	2	2	n/a
Module B	b	0.654	0.850	0.458	m
	d	0.191	0.191	0.191	m
Module C	c	0.541	0.703	0.379	m
	c_{offset}	0.0368	0.0368	0.0368	m
	θ	0.436	0.436	0.436	rad

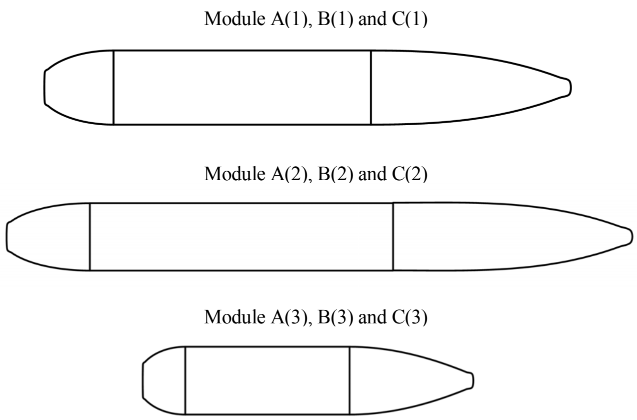

Figure 3. Modular section definition

The Myring hull can be divided into two or more modular sections and at any position in the design of AUV. For simplicity, in this paper we choose the three sections in the definition of the Myring hull in Fig. 2 as three modular sections: the nose section (Module A), the middle section (Module B) and the tail section (Module C). We defined three modules of A, B and C respectively as in TABLE I and Fig. 3. The hull configured by module A(1), B(1) and C(1) is chosen as the standard reference model. The Myring hull is adopted to verify the proposed standard reference model method with the theoretical values of the hydrodynamic coefficients of the hull calculated by empirical methods. As this hull contour is streamlined, its hydrodynamic coefficients can be obtained with empirical methods accurately.

B. Standard Reference Model Method and Results

The normal force curve slope is chosen to elaborate the standard reference model method. The offset values of the modular normal force curve slope from that of the reference modular sections are defined as follows.

$$\begin{aligned}
&\bar{C}_{N_\alpha}\left(A(i)\right) = C_{N_\alpha}\left(A(i)\right) - C_{N_\alpha}\left(A(1)\right), (i = 1,2,3) \\
&\bar{C}_{N_\alpha}\left(B(j)\right) = C_{N_\alpha}\left(B(j)\right) - C_{N_\alpha}\left(B(1)\right), (j = 1,2,3) \\
&\bar{C}_{N_\alpha}\left(C(k)\right) = C_{N_\alpha}\left(C(k)\right) - C_{N_\alpha}\left(C(1)\right), (k = 1,2,3)
\end{aligned} \tag{14}$$

Then we have,

$$\begin{aligned}
&\bar{C}_{N_\alpha}\left(A(i)\right) + \bar{C}_{N_\alpha}\left(B(j)\right) + \bar{C}_{N_\alpha}\left(C(k)\right) \\
&= C_{N_\alpha}\left(i,j,k\right) - C_{N_\alpha}\left(1,1,1\right), (i,j,k = 1,2,3\ ).
\end{aligned} \tag{15}$$

From the definition it is concluded that,

$$\bar{C}_{N_\alpha}\left(A(1)\right) = 0, \bar{C}_{N_\alpha}\left(B(1)\right) = 0, \bar{C}_{N_\alpha}\left(C(1)\right) = 0. \tag{16}$$

In order to calculate the values of the other six unknown offsets, the following six equations containing one unknown parameter are used.

$$\begin{aligned}
&\bar{C}_{N_\alpha}\left(A(i)\right) = C_{N_\alpha}\left(i,1,1\right) - C_{N_\alpha}\left(1,1,1\right), (i = 2,3) \\
&\bar{C}_{N_\alpha}\left(B(j)\right) = C_{N_\alpha}\left(1,j,1\right) - C_{N_\alpha}\left(1,1,1\right), (j = 2,3) \\
&\bar{C}_{N_\alpha}\left(C(k)\right) = C_{N_\alpha}\left(1,1,k\right) - C_{N_\alpha}\left(1,1,1\right), (k = 2,3)
\end{aligned} \tag{17}$$

After all the offsets from the reference modular sections are obtained, we can use these offset values and the normal force curve slope of the standard reference model to calculate the normal force curve slope of any configuration from these modules by,

$$\begin{aligned}
&C_{N_\alpha}\left(i,j,k\right) \\
&= \bar{C}_{N_\alpha}\left(A(i)\right) + \bar{C}_{N_\alpha}\left(B(j)\right) + \bar{C}_{N_\alpha}\left(C(k)\right) + C_{N_\alpha}\left(1,1,1\right).
\end{aligned} \tag{18}$$

The proposed method is applied to all the five hydrodynamic coefficients in the normal-force axis system. And it is required that the values of these hydrodynamic coefficients of seven different configurations including the standard reference model indicated in (17) are known in advance to calculate the offsets from the reference modular sections, as the bold rows in TABLE VII. The offset values calculated by (17) are listed in TABLE II-VI. The values of the hydrodynamic coefficients estimated with the proposed method are compared with their theoretical values in TABLE VII, where the 'm' outside the bracket means values estimated from the standard reference method and the 'E' outside the bracket means relative errors of the related coefficients in percentage. For the Myring hulls configured from the modular sections defined in TABLE I the relative errors of the estimated values are less than 4% for the normal force coefficients, less than 6% for the drag coefficient, and generally no more than 10% for the moment coefficients with only one exception of $C_{m_q}\left(3,3,3\right)$. The estimated values of the normal force coefficients are more accurate than that of the moment coefficients, which is due to the fact that in order to make the standard reference model method practical for the moment hydrodynamic coefficients the distance related terms in (9) and (10) are ignored.

TABLE II. OFFSETS OF THE NORMAL FORCE CURVE SLOPE

i, j, k	$\bar{C}_{N_\alpha}\left(A(i)\right)$	$\bar{C}_{N_\alpha}\left(B(j)\right)$	$\bar{C}_{N_\alpha}\left(C(k)\right)$
2	0.035365	0.12516	0.10353
3	-0.035343	-0.12524	0.11172

TABLE III. OFFSETS OF THE NORMAL FORCE PITCHING DERIVATIVE

i, j, k	$\bar{C}_{N_q}(A(i))$	$\bar{C}_{N_q}(B(j))$	$\bar{C}_{N_q}(C(k))$
2	0.045418	0.19428	0.15862
3	-0.044236	-0.17361	-0.023181

TABLE IV. OFFSETS OF THE MOMENT CURVE SLOPE

i, j, k	$\bar{C}_{m_\alpha}(A(i))$	$\bar{C}_{m_\alpha}(B(j))$	$\bar{C}_{m_\alpha}(C(k))$
2	0.36253	0.94844	0.80946
3	-0.49369	-1.0003	-1.0477

TABLE V. OFFSETS OF THE MOMENT PITCHING DERIVATIVE

i, j, k	$\bar{C}_{m_q}(A(i))$	$\bar{C}_{m_q}(B(j))$	$\bar{C}_{m_q}(C(k))$
2	-0.0068183	-0.022312	-0.018334
3	0.0083833	0.02026	0.021939

TABLE VI. OFFSETS OF THE PRESSURE-DRAG COEFFICIENT

i, j, k	$\bar{C}_{D_p}(A(i))$	$\bar{C}_{D_p}(B(j))$	$\bar{C}_{D_p}(C(k))$
2	-0.0027738	-0.0082346	-0.0069197
3	0.0030453	0.010713	0.0092303

TABLE VII. ESTIMATED HYDRODYNAMIC COEFFICIENTS COMPARED WITH THEORETICAL VALUES

A(*i*)	B(*j*)	C(*k*)	$C_{N\alpha}$	$(C_{N\alpha})_m$	$(C_{N\alpha})_E$ %	C_{Nq}	$(C_{Nq})_m$	$(C_{Nq})_E$ %	$C_{m\alpha}$	$(C_{m\alpha})_m$	$(C_{m\alpha})_E$ %	C_{mq}	$(C_{mq})_m$	$(C_{mq})_E$ %	C_{D0}	$(C_{D0})_m$	$(C_{D0})_E$ %
1	*1*	*1*	**1.15**	**1.15**	**0**	**0.736**	**0.736**	**0**	**5.90**	**5.90**	**0**	**-0.082**	**-0.082**	**0**	**0.139**	**0.139**	**0**
2	*1*	*1*	**1.19**	**1.19**	**0**	**0.781**	**0.781**	**0**	**6.26**	**6.26**	**0**	**-0.089**	**-0.089**	**0**	**0.140**	**0.140**	**0**
3	*1*	*1*	**1.12**	**1.12**	**0**	**0.692**	**0.692**	**0**	**5.40**	**5.40**	**0**	**-0.074**	**-0.074**	**0**	**0.137**	**0.137**	**0**
1	*2*	*1*	**1.28**	**1.28**	**0**	**0.930**	**0.930**	**0**	**6.84**	**6.84**	**0**	**-0.105**	**-0.105**	**0**	**0.150**	**0.150**	**0**
2	*2*	*1*	1.31	1.31	0.0	0.980	0.975	-0.5	7.23	7.21	-0.3	-0.113	-0.111	-1.0	0.152	0.151	-0.4
3	*2*	*1*	1.24	1.24	0.0	0.881	0.886	0.5	6.30	6.35	0.8	-0.094	-0.096	1.8	0.148	0.148	0.5
1	*3*	*1*	**1.03**	**1.03**	**0**	**0.562**	**0.562**	**0**	**4.90**	**4.90**	**0**	**-0.062**	**-0.062**	**0**	**0.130**	**0.130**	**0**
2	*3*	*1*	1.06	1.06	0.0	0.602	0.608	0.8	5.23	5.26	0.5	-0.068	-0.069	1.6	0.131	0.132	0.8
3	*3*	*1*	0.99	0.99	-0.1	0.523	0.518	-1.0	4.45	4.40	-1.2	-0.055	-0.054	-2.8	0.130	0.129	-1.0
1	*1*	*2*	**1.25**	**1.25**	**0**	**0.894**	**0.894**	**0**	**6.70**	**6.70**	**0**	**-0.101**	**-0.101**	**0**	**0.148**	**0.148**	**0**
2	*1*	*2*	1.29	1.29	0.0	0.944	0.940	-0.4	7.09	7.07	-0.3	-0.108	-0.107	-0.9	0.150	0.149	-0.3
3	*1*	*2*	1.22	1.22	0.0	0.846	0.850	0.5	6.17	6.21	0.7	-0.091	-0.092	1.6	0.146	0.146	0.4
1	*2*	*2*	1.38	1.38	0.1	1.104	1.089	-1.4	7.61	7.65	0.5	-0.124	-0.123	-1.2	0.160	0.159	-0.7
2	*2*	*2*	1.41	1.41	0.2	1.157	1.134	-2.0	8.02	8.02	-0.1	-0.133	-0.130	-2.8	0.162	0.160	-1.2
3	*2*	*2*	1.34	1.34	0.1	1.052	1.044	-0.7	7.02	7.16	2.0	-0.113	-0.115	1.5	0.157	0.157	-0.1
1	*3*	*2*	1.13	1.13	0.0	0.704	0.721	2.4	5.75	5.70	-0.7	-0.079	-0.080	2.2	0.137	0.139	1.6
2	*3*	*2*	1.16	1.16	0.0	0.748	0.766	2.4	6.11	6.07	-0.6	-0.085	-0.087	2.2	0.139	0.141	1.6
3	*3*	*2*	1.09	1.09	0.0	0.660	0.677	2.4	5.26	5.21	-1.0	-0.071	-0.072	2.0	0.136	0.138	1.5
1	*1*	*3*	**1.26**	**1.26**	**0**	**0.713**	**0.713**	**0**	**4.85**	**4.85**	**0**	**-0.060**	**-0.060**	**0**	**0.134**	**0.134**	**0**
2	*1*	*3*	1.31	1.30	-0.6	0.763	0.758	-0.6	5.16	5.21	1.0	-0.066	-0.067	2.2	0.135	0.136	0.7
3	*1*	*3*	1.22	1.23	0.6	0.664	0.668	0.7	4.42	4.35	-1.6	-0.054	-0.052	-3.4	0.134	0.132	-0.8
1	*2*	*3*	1.41	1.39	-1.9	0.928	0.907	-2.3	5.67	5.80	2.2	-0.078	-0.083	5.3	0.143	0.145	1.5
2	*2*	*3*	1.46	1.42	-2.3	0.984	0.952	-3.2	6.00	6.16	2.6	-0.085	-0.089	5.4	0.145	0.147	1.5
3	*2*	*3*	1.37	1.35	-1.4	0.874	0.863	-1.3	5.20	5.30	2.0	-0.070	-0.074	5.4	0.141	0.143	1.6
1	*3*	*3*	1.11	1.14	2.3	0.523	0.539	3.0	3.95	3.85	-2.6	-0.044	-0.040	-8.6	0.130	0.125	-3.3
2	*3*	*3*	1.15	1.17	1.6	0.567	0.584	3.1	4.24	4.21	-0.8	-0.048	-0.047	-3.0	0.128	0.127	-1.1
3	*3*	*3*	1.07	1.10	2.9	0.481	0.495	2.8	3.57	3.35	-6.1	-0.039	-0.032	-18.0	0.132	0.124	-6.0

VI. CONCLUSIONS

It is concluded from the results that theoretically the standard reference model method could give good estimation of the values of the hydrodynamic coefficients of the hull by the offsets from reference modular sections in the normal-force axis system. In the future research, we will apply the proposed method on the STARFISH AUV [11] whose payload configuration changes frequently based on different mission requirements. First, we will try to establish a parameter list for each modular section of the STARFISH AUV. This will allow us to generate the dynamic model for AUV with different configurations more accurately than the pure empirical methods, and faster than the tested based methods..

ACKNOWLEDGMENT

The authors would like to thank the STARFISH project team members for their support and sharing the experimental data.

REFERENCES

[1] N. A. Cruz and A. C. Matos, “The MARES AUV, a modular autonomous robot for environment sampling,” OCEANS 2008. 2008.

[2] J. Ferguson and A. Pope, “Explorer-a modular AUV for commercial site survey,” Underwater Technology, 2000. UT 00. Proceedings of the 2000 International Symposium on. 2000.

[3] M. Sibenac, “Modular AUV for routine deep water science operations,” OCEANS '02 MTS/IEEE. 2002.

[4] T. I. Fossen, “Guidance and Control of Ocean Vehicles,” 1999, New York: Wiley.

[5] O. M. Faltinsen, “Sea Loads on Ships and Offshore Structures,” 1990: Cambridge University Press.

[6] A. I. Korotkin. “Added Masses of Ship Structures,” Springer Science Business Media. B. V. 2009.

[7] D. E. Hoak, “The USAF Stability and Control DATCOM, in TR-83-3048,” 1978, Air Force Wright Aeronautical Laboratories.

[8] T. Prestero, “Verification of a Six-Degree of Freedom Simulation Model for the REMUS Autonomous Underwater Vehicle,” 2001, Massachusetts Institute of Technology. p. 120.

[9] Y. L. Fill, “Implementation and test of ISiMI100 AUV for a member of AUVs Fleet,” OCEANS 2008. 2008.

[10] L. R. Fisher, “Equations and Charts for Determining the Hypersonic Stability Derivatives of Combinations of Cons Frustums Computed by Newtonian Impact Theory,” NASA TN D-149, 1959. (U)

[11] T. B. Koay, Y. T. Tan, Y. H. Eng, R. Gao, M. Chitre, J. L. Chew, N. Chandhavarkar, R. Khan, T. Taher, and J. Koh, “STARFISH - A small team of autonomous robotics fish,” in 3rd International Conference on Underwater System Technology: Theory and Applications 2010, (Cyberjaya, Malaysia), Nov 2010.