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TRAJECTORY AND ATTITUDE CONTROL OF AN UNDERWATER TOWED VEHICLE

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ABSTRACT

A new concept of control technique to perform operation of trajectory maneuvering to a controllable underwater towed vehicle moving in a designated path with a required attitude is presented. A trajectory and attitude control technique for the towed vehicle is proposed in order to accomplish the vehicle's trajectory and attitude manipulations. This technique is based on a fuzzy algorithm. The towed vehicle in the research consists of a cylindrical main body equipped with several active horizontal and vertical control surfaces. Numerical simulation on the hydrodynamic and control behavior of the towed vehicle under this control manipulation is conducted based on a fully 3-D hydrodynamic model of an underwater towed vehicle. In the model the governing equation of the towed cable is based on the Ablow and Schechter method. The six-degrees-of-freedom equations of motion for an underwater vehicle simulation proposed by Gertler and Hagen are adopted to estimate the hydrodynamic performance of the towed vehicle. In numerical simulation the deflections of vehicle's control surfaces are governed by the proposed fuzzy controller to manipulate the vehicle traveling along a 3-D stipulated trajectory configuration and required attitude. The values of the deflections are taken as input parameters for the hydrodynamic model at every time step. The performance of the towed vehicle under different designated trajectory and attitude control manipulations can then be investigated with the hydrodynamic model.

INTRODUCTION

A controllable underwater towed system is an active undersea survey apparatus which is extensively used for ocean observation and ocean research. The underwater towed vehicle is the key equipment in the towed system. Before a new controllable underwater towed vehicle is put forward, it is generally required that forecast of hydrodynamic and control behavior of the towed vehicle in a mathematical or experimental way should first be made so that the towed vehicle with better hydrodynamic and control performances can be developed.

In study on hydrodynamic and control performance of an underwater towed vehicle, although several mathematical models and experimental approaches have been proposed to predict the control behavior of an underwater towed vehicle (Koterayama, et al., 1988, 1995; Wu and Chwang, 2001), the research on the control performance of an underwater towed vehicle today is mainly concentrated on the hydrodynamic prediction when the control manipulations to the towed vehicle have been determined. In this kind of approach the trajectory and attitude of an underwater towed vehicle are predicted only on the condition that definite control manipulations to the towed vehicle have been determined, these manipulations may include altering the length of the towed cable of the system, changing the deflections of the vehicle control surfaces or maneuvering the attitude control mechanisms of the vehicle. But what control manipulations to the underwater towed vehicle should be taken in order that the vehicle can travel along a specified orbit with a demanded attitude, this inverse problem remains less studied at present.

The progress of fuzzy algorithm and neural network control technique in recent years provides a new developing space to deal with this kind of control task. In this aspect, Kato (1991, 1992) made valuable attempt on observation of the possibility of trajectory and attitude control of a controllable underwater towed vehicle. In his research a towed vehicle in an average operating depth of 500 m is taken as the object of study, the control technique applied in his research is on the basis of fuzzy algorithm, numerical simulation results of trajectory and attitude control to the towed vehicle by adjusting vehicle horizontal and vertical control surfaces with fuzzy control theory are presented. But the emphasis of his research is on vehicle control problem and to present a qualitative analysis and mechanism discussion on the vehicle trajectory and attitude technique, the hydrodynamic model of the whole underwater towed system is established in a relative rough way.

In this paper the results of numerical simulation on the hydrodynamic and control behavior of a controllable underwater towed vehicle under trajectory and attitude control manipulations are presented. The simulation is conducted based on a fully 3-D hydrodynamic model of an underwater towed system. After the hydrodynamic model is established, a trajectory and attitude controller for the vehicle trajectory and attitude maneuvering is integrated into the hydrodynamic model to constitute a hydrodynamic and control model for the towed vehicle. During numerical simulations the deflections of vehicle's control surfaces are governed by the proposed controller to manipulate the vehicle traveling along a stipulated trajectory configuration with a demanded attitude. In numerical simulation the values of the control surface deflections are taken as input data for the hydrodynamic and control model, the output data of the model is the hydrodynamic response under these control manipulations. In this way the dynamic behavior of the controllable underwater towed vehicle can be observed numerically.

OUTLINE OF THE RESEARCH PROBLEM

To discuss the control technique applied in the vehicle control, a fully three-dimensional hydrodynamic model of a controllable underwater towed system is first presented. The controllable underwater towed vehicle in the research consists of a cylindrical main body with several active control surfaces. Maneuvering of the towed vehicle is achieved by changing the deflections of the control surfaces. The controllable underwater towed vehicle applied in this research is presented in a schematic drawing as shown in Fig. 1. The principal dimensions of the towed vehicle and towed cable are shown in Table 1.

Table 1 Principal dimensions of the towed system

Cable:

diameter = *0.015 m* , length = *600 m*,
mass per unit length = *2.5 kg/m*,

Towed vehicle:

$x_T = -0.5\,m$, $y_T = 0.0\,m$, $z_T = -0.3\,m$, mass = *530 kg.*

Main body:

diameter = *0.4 m*, length = *2.5 m*

control surfaces:

horizontal main wing: chord = *0.7 m*, span = *2.3 m*, $y_i = z_i = 0,\ x_i = -0.5\,m$

horizontal tail wing: chord = *0.5 m*, span = *1.6m*, $y_i = z_i = 0,\ x_i = 1.0\,m$,

vertical tail wing: chord = 0.5 m, span = 1.4 m, $y_i = z_i = 0,\ x_i = 1.0\,m$,

In Table 1 (x_T, y_T, z_T) are the towing point coordinates of the towed vehicle in the vehicle-fixed frame, and (x_i, y_i, z_i) hydrodynamic reference point position of the control surfaces in the vehicle-fixed frame.

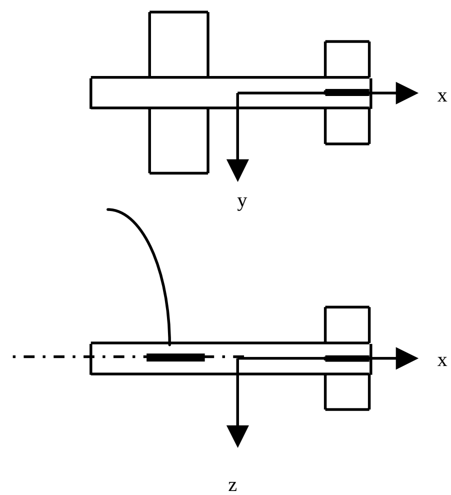

Fig. 1 The controllable underwater towed vehicle

In the study, the equation of motion for the towed cable is established based on the Ablow and Schechter (1983) method. The hydrodynamic behavior of the underwater vehicle is described by the six-degrees-of-freedom equations of motion for submarine simulation proposed by Gertler and Hagen (1967). The hydrodynamic loadings on the towed vehicle are considered to be sum of inertial and viscous forces. In establishing the hydrodynamic model of the towed system, the governing equation for the cable is given first, the speed of the towing ship at water surface and the dynamic equations of the towed vehicle are taken as the boundary conditions for the governing equations for the cable. After the boundary conditions at the both ends of the cable have been determined, the governing equations for the towed system can be established. A control algorithm or a controller based on fuzzy algorithm for vehicle trajectory and attitude maneuvering is subsequently introduced to the governing equation of the towed system thus an integrated hydrodynamic and control model of the towed vehicle is constructed. For the numerical simulation presented in the paper, computation starts from a steady solution with no unsteady control manipulations to the vehicle is taken as the initial condition for the hydrodynamic and control model, and Burgess's algorithm (1991) is adopted to approximate the hydrodynamic and control model in a finite difference mathod.

The hydrodynamic and control model established in this way determines the parameters of the towed vehicle and towed cable completely. Once the velocity of the towing ship and the control surface deflections governed by the proposed control algorithm, the dynamic properties of the towed vehicle under a given trajectory and attitude control can be predicted completely, thereby the effectiveness of the control technique can be observed.

HYDRODYNAMIC MODEL OF THE UNDERWATER TOWED SYSTEM

The underwater towed system described in this paper consists of a single towed cable with its controllable underwater towed vehicle. Three different coordinate systems are used in derivation of the hydrodynamic model, i.e. the fixed inertial coordinate system (X, Y, Z), local coordinate systems for the cable (t, n, b) and for the underwater towed vehicle (x, y, z) as shown in Figs. 1 and 2. In this research the equation of motions for the towed cable and towed vehicle are given separately and then combined together to form the hydrodynamic model of the underwater towed system.

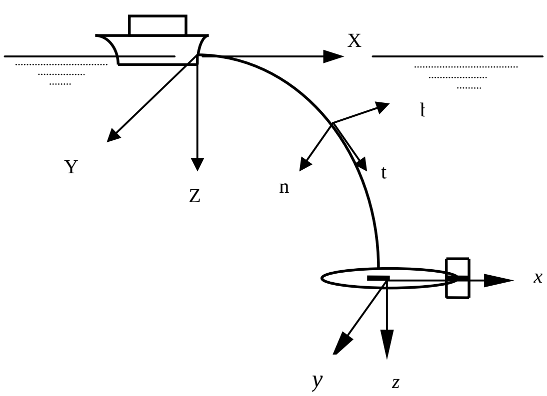

Fig. 2 Three different coordinate systems

Equations of motion for the cable

The equations of motion for cable can be described by a finite difference method (Wu and Chwang, 2000). They can be written in a matrix form as

$$MY' = N\dot{Y} + Q\,,$$
$$Y = (T, v_t, v_n, v_b, \vartheta, \varphi)^T\,,\quad Y' = \frac{\partial Y}{\partial s}\,,\qquad \dot{Y} = \frac{\partial Y}{\partial t}\,, \qquad (1)$$

where T denotes the tension force of a cable, v_t, v_n and v_b are three velocity components in the local coordinates of the cable, ϑ and φ are the relative orientations of the local frame of the cable to the inertial frame, s is the unstretched cable length coordinate, M and N are square matrices of order 6, and Q is a column matrix of order 6. The expressions of matrices M, N and Q can be found in Wu and Chwang (2000).

At any point on the cable, the local frame of a cable (t, n, b) and the inertial frame (i, j, k) are related by

$$(\mathbf{t},\ \mathbf{n},\ \mathbf{b}) = (\mathbf{i},\ \mathbf{j},\ \mathbf{k})\,[\mathrm{D}], \qquad (2)$$

where $[D]$ is the transform matrix between the local frame of the cable and the inertial frame (Wu and Chwang, 2000).

Boundary conditions for the towed cable

The relation between the towing ship velocity and the towing point velocity of the cable is

$$[v_t, v_n, v_b] = [S_x, S_y, S_z][D], \qquad (3)$$

where S_x, S_y and S_z are the velocity components of the towing ship in inertial coordinates.

The velocity coupling relation between the end of the cable and the towing point of the towed vehicle is

$$[\boldsymbol{V}_0 + \boldsymbol{\varpi} \times \boldsymbol{r}_T] = [E][D]\boldsymbol{V}\,, \qquad (4)$$

where $\boldsymbol{V}_0 = (u, v, w)^T$ and $\boldsymbol{\varpi} =$ (p, q, r) are translational and angular velocities of the towed vehicle in the vehicle-fixed coordinates, $\boldsymbol{r}_T = (x_T, y_T, z_T)$ is the towing point coordinates in the vehicle-fixed frame, $\boldsymbol{V}$ is the velocity of the conjunction point between the towed vehicle and the towed cable expressed in local coordinates of the cable, and $[E]$ is the transform matrix between the local frame of the vehicle and the inertial frame (Abkowitz, 1969), and

$$[\mathrm{E}] = \begin{bmatrix} \cos\theta\cos\psi & \cos\theta\sin\psi & -\sin\theta \\ -\sin\psi\cos\phi + \sin\phi\sin\theta\cos\psi & \cos\phi\cos\psi + \sin\phi\sin\theta\sin\psi & \sin\phi\cos\theta \\ \sin\phi\sin\psi + \cos\phi\cos\psi\sin\theta & -\sin\phi\cos\psi + \cos\phi\sin\theta\sin\psi & \cos\phi\cos\theta \end{bmatrix}$$

where ϕ, θ and ψ are the roll, pitch and yaw angles of the underwater towed vehicle.

Equations of motion for the underwater towed vehicle

The hydrodynamic behavior of the towed vehicle in the model is described by the same six-degrees-of-freedom equations of motion for an underwater vehicle. The equations can be written in a vehicle-fixed coordinate system as (Gertler and Hagen, 1967)

$$m\left[\dot{u}-vr+wq-x_G(q^2+r^2)+y_G(pq-\dot{r})+z_G(pr+\dot{q})\right]=X\ , \tag{5}$$

$$m\left[\dot{v}+ur-wp+x_G(pq+\dot{r})-y_G(p^2+r^2)+z_G(qr-\dot{p})\right]=Y\ , \tag{6}$$

$$m\left[\dot{w}-uq+vp+x_G(pr-\dot{q})+y_G(qr+\dot{p})-z_G(p^2+q^2)\right]=Z\ , \tag{7}$$

$$\begin{aligned} I_X\dot{p}+(I_Z-I_Y)qr+I_{XY}(pr-\dot{q})-I_{YZ}(q^2-r^2)-I_{XZ}(pq+\dot{r}) \\ +m\left[y_G(\dot{w}-uq+vp)-z_G(\dot{v}+ur-wp)\right]=K, \end{aligned} \tag{8}$$

$$\begin{aligned} I_Y\dot{q}+(I_X-I_Z)pr-I_{XY}(qr+\dot{p})+I_{YZ}(pq-\dot{r})+I_{XZ}(p^2-r^2) \\ -m\left[x_G(\dot{w}-uq+vp)-z_G(\dot{u}-vr+wq)\right]=M, \end{aligned} \tag{9}$$

$$\begin{aligned} I_Z\dot{r}+(I_Y-I_X)pq-I_{XY}(p^2-q^2)-I_{YZ}(pr+\dot{q})+I_{XZ}(qr-\dot{p}) \\ +m\left[x_G(\dot{v}+ur-wp)-y_G(\dot{u}-vr+wq)\right]=N, \end{aligned} \tag{10}$$

where the left-hand sides represent inertial forces and moments and the right-hand sides denote external forces on an underwater vehicle. The symbols in the equations are based on the standard notation. It is assumed that the external forces $\boldsymbol{F}_0=(X,Y,Z)^T$ and moments $\boldsymbol{M}_0=(K,M,N)^T$ on a vehicle are composed of restoring forces, fluid inertial forces, viscous forces, towing forces and their corresponding moments. Therefore

$$\boldsymbol{F}_0=\boldsymbol{F}_W+\boldsymbol{F}_I+\boldsymbol{F}_V+\boldsymbol{F}_T\ , \tag{11}$$

$$\boldsymbol{M}_0=\boldsymbol{M}_W+\boldsymbol{M}_I+\boldsymbol{M}_V+\boldsymbol{M}_T\ , \tag{12}$$

where subscript W represents hydrostatic restoring forces, I fluid inertial forces, V forces arising from viscosity and T towing forces.

In Eqs. 11 and 12 the hydrostatic restoring force and moment $\boldsymbol{F}_W$ and $\boldsymbol{M}_W$ are produced from the joint effect of vehicle weight and buoyancy, the towing force and moment $\boldsymbol{F}_T$ and $\boldsymbol{M}_T$ on the towed vehicle in local coordinates of the vehicle are determined from the coupled relation between the towed cable and the towed vehicle, the fluid inertial force and moment $\boldsymbol{F}_I$ and $\boldsymbol{M}_I$ are described by the products of vehicle's accelerations and vehicle's added masses whose values are determined from computations of three dimensional potential theory in an unbounded fluid using a panel method, the viscous force and moment $\boldsymbol{F}_V$ and $\boldsymbol{M}_V$ on the vehicle are sum of those on individual control surfaces and on a fuselage by neglecting their interactions (Nahon, 1996). The detail of evaluation on $\boldsymbol{F}_I$, $\boldsymbol{M}_I$, $\boldsymbol{F}_V$ and $\boldsymbol{M}_V$ can be found in Wu and Chwang (2001).

The Rate of Change of Euler Angles for the Vehicle

To complete the hydrodynamic model of an underwater vehicle, the expressions for the rate of change of Euler angles for the vehicle are given by

$$\dot{\phi}=p+q\sin\phi\tan\theta+r\cos\phi\tan\theta\ , \tag{13}$$

$$\dot{\theta}=q\cos\phi-r\sin\phi\ , \tag{14}$$

$$\dot{\psi}=q\frac{\sin\phi}{\cos\theta}+r\frac{\cos\phi}{\cos\theta}\ . \tag{15}$$

where p, q and r the angular velocities of the towed vehicle in the vehicle-fixed coordinates.

DESIGN OF THE FUZZY CONTROLLER

The purpose of the fuzzy controller design is to generate a control algorithm for manipulation of the vehicle being towed along a stipulated depth trajectory configuration with a demanded pitching attitude. The theoretical approach for the controller's design applied in this research is based on a fuzzy algorithm, the error and the rate of change for error are regarded as input parameters for the controller, these parameters are carried out for fuzzification treatment according to given membership function, fuzzy control quantities are calculated by fuzzy reasoning method, finally these fuzzy control quantities are transferred to precise ones under defuzzification process. The output precise control quantities by the controller are then taken as control commands to adjust the vehicle's control surfaces for fulfilling a trajectory and attitude control duties. The hydrodynamic response under the control manipulation is estimated by the numerical simulation of the hydrodynamic model as described in preceding section. Structure of the fuzzy controller applied in the research is shown in Fig. 3.

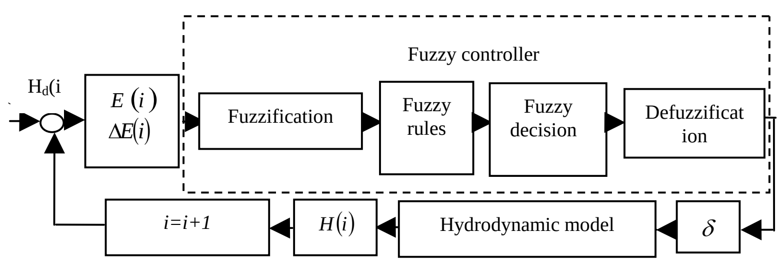

Fig. 3 Structure of the fuzzy controller

In Fig. 3 $H_d(i)$ is a commanded signal, $E(i)$ and $\Delta E(i)$ are the error and the rate of change of error, $\delta(i)$ is an output precise control quantity by the fuzzy controller, and $H(i)$ is the hydrodynamic response under the control manipulation. In our research $H_d(i)$ represents a commanded submerged depth $h_d(i)$ or a pitching angle $\theta_d(i)$ of the vehicle, $E(i)$ denotes the error of vehicle's submerged depth $E_h(i)$ or the error of its pitching angle $E_\theta(i)$, $\Delta E(i)$ means the corresponding rate of change $\Delta E_h(i)$ or $\Delta E_\theta(i)$, δ is the deflection of horizontal main wing $\delta_m(i)$ or the deflection of horizontal tail wing $\delta_t(i)$, and $H(i)$ are numerical outputs of submerged depth $h(i)$ and pitching angle $\theta(i)$ of the towed vehicle via numerical computation of the hydrodynamic model, *i* manifests time step,

$$E_h(i) = h_d(i) - h(i), \tag{16}$$

$$E_\theta(i) = \theta_d(i) - \theta(i), \tag{17}$$

$$\Delta E_h(i) = \frac{h_d(i) - h(i)}{t_i - t_{i-1}}, \tag{18}$$

$$\Delta E_\theta(i) = \frac{h_\theta(i) - \theta(i)}{t_i - t_{i-1}}, \tag{19}$$

Input/output variables, universe of discourse and membership function

In this research input variables to the fuzzy controller are $E_h(i)$, $\Delta E_h(i)$ and $E_\theta(i)$, $\Delta E_\theta(i)$. The output control quantities are $\delta_m(i)$ and $\delta_t(i)$. Universe of discourse of input/output is quantized into 19 grades

$$\{-9, -8, \cdots, 0, \cdots, 8, 9\},$$

input and output variables are partitioned into 7 fuzzy sets: Negative Big (*NB*), Negative Middle (*NM*), Negative Small (*NS*), Zero (*ZO*), Positive Small (*PS*), Positive Medium (*PM*), Positive Big (*PB*). Isosceles triangle is applied as the membership function of input and output sets.

Determination of fuzzy control rule

The fuzzy control rules applied in this research are constituted by a series of IF-THEN fuzzy condition statements. The fuzzy control rules designed by our programming are shown in Table 2

Table 2 The designed fuzzy control rules

δ		E						
		NL	*NM*	*NS*	*ZO*	*PS*	*PM*	*PL*
ΔE	NL	*PL*	*PL*	*PL*	*PL*	*PS*	*PM*	*ZO*
	NM	*PL*	*PL*	*PL*	*PS*	*PM*	*ZO*	*NM*
	NS	*PL*	*PL*	*PS*	*PM*	*ZO*	*NM*	*NS*
	ZO	*PL*	*PS*	*PM*	*ZO*	*NM*	*NS*	*NL*
	PS	*PS*	*PM*	*ZO*	*NM*	*NS*	*NL*	*NL*
	PM	*PM*	*ZO*	*NM*	*NS*	*NL*	*NL*	*NL*
	PL	*ZO*	*NM*	*NS*	*NL*	*NL*	*NL*	*NL*

Defuzzification

The input fuzzy variables are reasoned by the fuzzy controller via inclusion and reasoning rules of fuzzy logic. The output obtained in this way is a fuzzy set. It should be transferred to a precise quantity by a defuzzification process so that a control manipulation to the towed vehicle can be achieved. In this paper barycentric method is adopted for defuzzification, that is,

$$x_0 = \frac{\sum_{i=1}^{19} x_i \mu(x_i)}{\sum_{i=1}^{19} \mu(x_i)}, \tag{20}$$

where x_i is the element of universe of discourse, $\mu(x_i)$ the value of membership, x_0 a decision result solved from the output fuzzy set.

NUMERICAL SOLUTION OF THE HYDRODYNAMIC AND CONTROL MODEL

The governing equation of cable (1) with the conditions described in previous section determines the towed system parameters completely. In this study the partial differential equation (1) is approximated by a finite difference equation centered in time and in space. The cable is divided into a series of segments of length ΔS_j and time is divided into a series of time steps Δt. The node number in the cable is 0 to N, 6 node variables $Y_j = (T, v_t, v_n, v_b, \vartheta, \varphi)_j^T$ $(j = 0 \sim N)$ are included at each node of cable. The finite difference approximation of equation (1) is written at mid point of each cable segment (Burgess 1991),

$$\left[M_{j+1}^{i+1}+M_{j}^{i+1}\right]\frac{Y_{j+1}^{i+1}-Y_{j}^{i+1}}{\Delta S_{j}}+\left[M_{j+1}^{i}+M_{j}^{i}\right]\frac{Y_{j+1}^{i}-Y_{j}^{i}}{\Delta S_{j}}= \tag{21}$$

$$\left[N_{j+1}^{i+1}+N_{j+1}^{i}\right]\frac{Y_{j+1}^{i+1}-Y_{j+1}^{i}}{\Delta t}+\left[N_{j}^{i+1}+N_{j}^{i}\right]\frac{Y_{j}^{i+1}-Y_{j}^{i}}{\Delta t}+Q_{j+1}^{i+1}+Q_{j}^{i+1}+Q_{j+1}^{i}+Q_{j}^{i},$$

where superscript i denotes i-th time step. The finite difference equations include all node variables in the cable, there are $6(N+1)$ unknown variables Y_j along the cable with $6N$ finite difference equations in Eq. (21). The rest 6 scalar equations are provided by Eqs (3) and (4) in finite difference form. However, Eq. (4) introduce 9 new variables, that is, 3 translational velocity components (*u, v, w*), 3 angular velocity components (*p, q, r)* and 3 Euler angles (ϕ,θ,ψ) of the towed vehicle. Therefore, 9 more equations are needed to solve the problem. These 9 equations are given by Eqs (5) to (10) and (13) to (15). The finite difference equations established can then be solved in time domain.

After the 3-D hydrodynamic model of an underwater towed system and corresponding algorithm are established, the trajectory and attitude controller for the towed vehicle is then integrated into the hydrodynamic model forming a hydrodynamic and control model for the towed vehicle. In numerical simulation on trajectory and attitude control to the vehicle, deflections of the vehicle's control surfaces are adjusted at every time step under the control commands from the proposed controller to meet the requirement of trajectory and attitude towing task. The values of the deflections of control surfaces are taken as input control parameters for the hydrodynamic and control model and the dynamic behavior of the controllable underwater towed vehicle under the control manipulations can be described by the proposed model. A brief outline of the computational procedure to describe the hydrodynamic and control behavior of the underwater towed vehicle under trajectory and attitude control manipulations is given below.

(1) Input particulars of an underwater towed system which include the geometric and physical data of the towed cable and towed vehicle.

(2) Calculate the steady state solution of the towed system.

(3) Introduce towing ship motion at time step i+1.

(4) Solve the hydrodynamic and control model in finite difference form for the towed system as described above and output the vehicle's submerged depth $h(i+1)$ and pitching angle $\theta(i+1)$ at the time step i+1.

(5) Let i=i+1 and go to Step 6 if the simulation is not completed; otherwise output the simulation results and end the program.

(6) Present the commanded submerged depth $h_d(i)$ and pitching angle at time step i.

(7) Determine the error and rate of change of error $E_h(i)$, $E_\theta(i)$, $\Delta E_h(i)$ and $\Delta E_\theta(i)$ by Eqs. 16 to 19.

(8) Determine the deflections of horizontal main wing and horizontal tail wing $\delta_m(i)$ and $\delta_t(i)$ by the fuzzy controller based on the data at Step 7. The values of the control surface deflections determined in this step are utilized to calculate the viscous force and moment $\boldsymbol{F}_V$ and $\boldsymbol{M}_V$ on the vehicle as described in Eqs. 11 and 12.

(9) Go to Step 3.

A flow-chart to summarize the computational and logical steps of the numerical simulation is shown in Fig. 4.

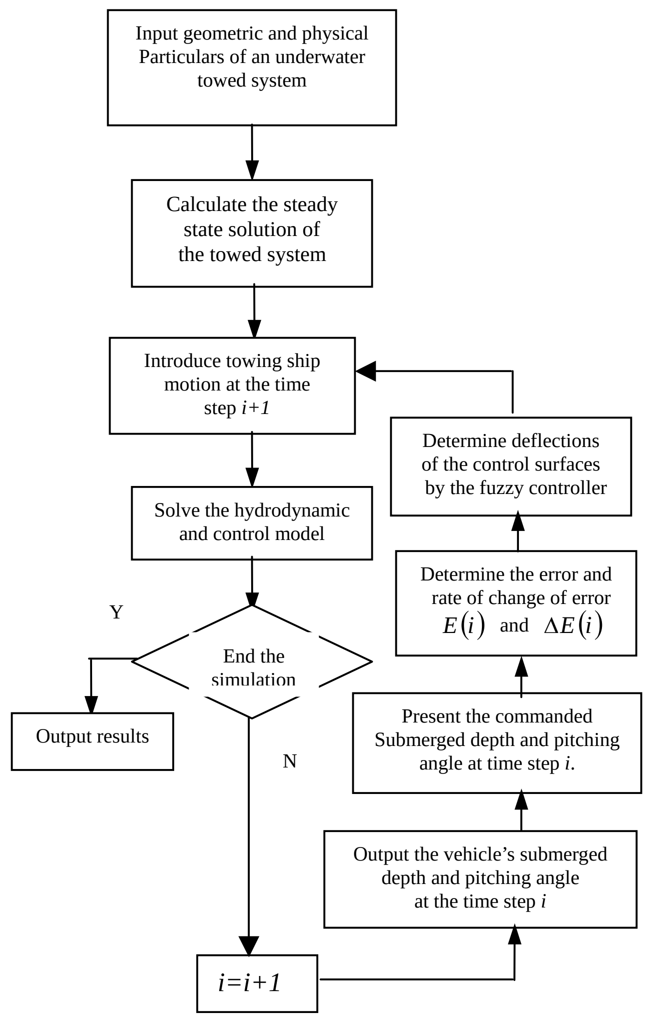

Fig. 4 A flow-chart to summarize the logical steps of the simulation

NUMERICAL SIMULATION OF TRAJECTORY AND ATTITUDE CONTROL TO THE TOWED VEHICLE

The trajectory and attitude control technique proposed above is applied to analyze the hydrodynamic and control behavior of a controllable underwater towed vehicle with the established hydrodynamic and control model. In numerical simulation the towing trajectory and attitude are first pre-designated, to meet the commanded requirement of trajectory and attitude manipulation is regarded as the control objective and adjustment of deflections of the vehicle's control surfaces is considered to be a major control means to accomplish the control towing task. Trajectory and attitude control to the towed vehicle is simulated numerically according to the control objective to observe the dynamic performance of the vehicle under this kind of control manipulation. The towed vehicle investigated in this paper is assumed to be a circular cylindrical main body equipped with a main horizontal control wing, a horizontal and vertical tail wings. Deflections of the main horizontal control wing and the horizontal tail wing are adjustable while the vertical tail wing is maintained vertically fixed to keep the vehicle attitude stable in vertical plane. Principal dimensions of the vehicle applied in numerical example are given in Table 1.

Numerical simulation is carried out with the model and the controllable underwater towed vehicle as described above to observe the validity of maneuvering the towed vehicle traveling along a specified trajectory with a commanded attitude by the proposed fuzzy controller. The simulation is conducted under a condition of straight towing with a constant velocity of 3.14 m/s. A sinusoidal towing orbit is first assigned. A steady towing condition of 253.6 m of vehicle's submerged depth with 7 degrees of horizontal main wing deflection and 0.4 degree of horizontal tail wing deflection is taken as the initial condition for the simulation. The objective of the control operation is to manipulate the vehicle traveling in the specified trajectory with a zero pitching angle. In the towing operation, depth trajectory control to the vehicle is mainly achieved by adjusting the deflection of the horizontal main wing and the pitching angle maintaining is mainly accomplished by governing the deflection of horizontal tail wing. The numerical control operations are performed every 0.1 second in the simulation. Manipulation to the vehicle control surfaces for fulfilling the control task by the fuzzy controller goes into effect after a steady towing of 300 seconds. The commanded sinusoidal towing orbit applied in the numerical example is written as

$$h_d = h_0 + A_0 \sin\left(\frac{2\pi}{T_0} t\right), \qquad t \ge 300 \qquad (22)$$

where h_0 is the vertical submerged depth in steady towing condition, A_0 the amplitude of the orbit, and T_0 the period. The values used in the numerical example are h_0 =253.6m, A_0 =10.0 m, T_0 =600 sec.

Fig. 5 shows a comparison of time histories between the depth trajectory of the vehicle under above describe control manipulation and the commanded one. From the result of Fig.5 it can be seen that the simulated trajectory agrees well with the commanded one, only small differences can be found between the simulated and commanded trajectories except for the initial stage of the control manipulation and the stage when the control towing operation is in smaller submerged depth phases. The whole control process is satisfactory. Fig. 6 illustrates the time histories of the vehicle pitching angle under the same control manipulation as that in Fig. 5. From the figure one can find that the pitching angle of the towed vehicle keeps almost zero degree, the amplitude of the pitching is less than one degree during the whole towing operation except for the initial stage of simulation. In order to implement the objective trajectory and attitude control, deflections of the horizontal main wing and the horizontal tail wing are adjusted by the fuzzy controller, their values during the control manipulation are demonstrated in Figs. 7 and 8. It is noticed from the figures that the variation patterns of the control surface deflections are similar with that of the vehicle depth trajectory as described in Fig. 5.

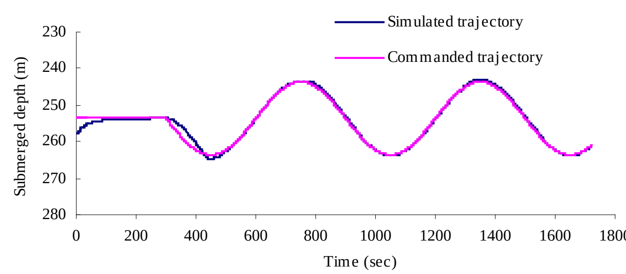

Fig. 5 Depth Trajectory control of the vehicle

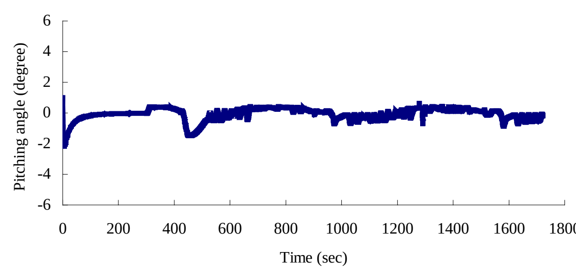

Fig. 6 Pitching angle of the vehicle

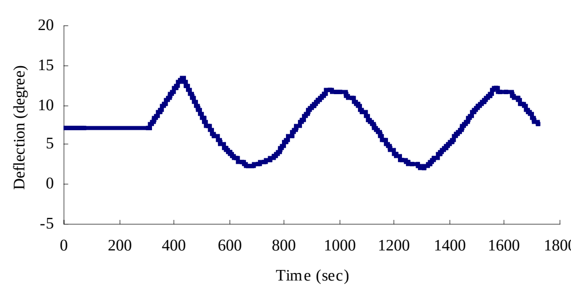

Fig. 7 Deflection of the horizontal main wing

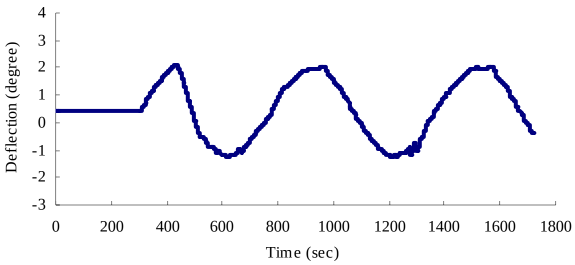

Fig. 8 Deflection of the horizontal tail wing

CONCLUSION

A control technique to implement trajectory and attitude manipulation for a controllable underwater towed vehicle is proposed and numerical simulation to observe hydrodynamic and control performance of the vehicle under the control manipulation is presented. The simulation is conducted based on a fully 3-D hydrodynamic model of an underwater towed system. After the hydrodynamic model is established, a fuzzy controller for the vehicle trajectory and attitude maneuvering is integrated into the hydrodynamic model to constitute a hydrodynamic and control model. By means of the model the control manipulation taken to the towed vehicle so that the vehicle can travel along a specified orbit with a demanded attitude is determined. The numerical simulation results of the control manipulations indicate that the proposed trajectory and attitude control technique to the towed vehicle based on the fuzzy control algorithm is feasible, the anticipative control objective can be fulfilled with the proposed control technique.

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