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Study on Manoeuverability and Control of an Autonomous Wave Adaptive Modular Vessel (WAM-V) for Ocean Observation

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Abstract— **In this paper, we are proposing the use of a catamaran equipped with standard navigational sensors as an autonomous surface vehicle for in situ measurement of oceanographic data or as a complimentary observing system. In this research, we mainly focus on the maneuverability of the Wave Adaptive Modular Vessel (WAM-V). The WAM-V must have ability to cruise on the water with a robust propulsion system which determines its propulsion capability and maneuverability. Firstly, the paper describes the configuration of WAM-V. Secondly the paper deals with mathematical modeling, which describes well physics based dynamics of WAM-V. Demand for WAM-V catamaran is justified to a point for improved manoeuverability and because the motion of the boat is affected by hydrodynamics, so many hydrodynamic parameters including resistance force for Mono hull and twin hull are estimated by towing tank experiment. It is observed from the experiments that at higher velocity (Froud Number (fn) > 0.3) due to interference between the two hulls the hydrodynamic derivatives do not remain same as in the case of a single hull. With the help of the geometrical shape of WAM-V the design ratios are calculated. The Matlab simulation is intended to analyze the different parameters for the effect of changing the propeller revolution which replaces the rudder action. Finally, the paper delineates the simulation results for PID tracking control of WAM-V using the Nomoto's response model.**

Keywords— Wave Adaptive Model (WAM-V), Marine Science Applications, Marine Robotics, Propelling and Turning Control, Captive Model Test and Dynamic Modelling of WAM-V.

I. INTRODUCTION

Negative impact of global climate change on the ocean environment cannot be overlooked anymore, a deep insight into the ocean environment and its environmental dynamics is needed to understand the ocean environmental behaviour and its effect on the society. According to research only 5% ocean, is known, and it is one of the most demanding environments and a vast frontier for discovery. Recent studies indicated that global warming and ocean acidification have worsened, and the frequency of the adverse impacts of climate changes has increased in recent years. Additionally, increase of human activity in the ocean and exploitation of the ocean resources has led to changes in the marine ecosystem and reduced fishery resources. Hence, in order to understand human intervention and its effect on the ocean environment, we need to nurture the next generation techniques. Currently oceanography or ocean environmental sensing (meteorological survey) is carried out using satellites, buoys, research vessels or ships. However, remote surveillance of oceanography data using satellites is restricted due to cloud cover, temporal/geographical coverage as well as spatial resolution. Meanwhile, manned research vessels are expensive for ocean surveillance, and in situ measurement of oceanographic data. Whereas the use of moored buoy, due to lack of controllability and self deployability is not so attractive option for spatial sampling purposes. Due to all of the above mentioned reasons autonomous surface vehicles (ASV) & autonomous underwater vehicles (AUV), due to their various capabilities for payload, communication, and autonomy, have emerged as the best option for in situ measurement of oceanography data as well as a complimentary observing system (port protection, mine countermeasures, and surveillance missions).

ASV are relatively a new technology; because of the exponential advancement in the technology, miniaturization and reduction in the power consumption of computational hardware and the sensors circuitry, further advancement in the ASV technology has been achieved. Nowadays, several designs of autonomous surface craft like monohull, catamaran, trimaran, streamlined, troller monohull and swath has been developed to maximize the surreptitious capabilities of performing marine operations. Catamarans, a vessel formed of two hulls or floats held side by side in a frame above them; either sail powered or propeller powered depending on the user requirement; allow for tremendous control in tight with their effortless driving hull form and lightweight. Cruising catamaran will be 20-30% faster than a cruising monohull of the same length. Now when it comes to performance, design factors such as payload capacity, stability and speed often plays an important role; a catamaran has a great benefit as it heels less and better load carrier with twinhull easy maneuverable. Maritime RobotX challenge is an ideal benchmark for the development of autonomous water craft (Catamaran-WAM-V) [1]. The competition held at Marina Bay in Singapore, was jointly organized by the National University of Singapore, Science Center Singapore and the Association for Unmanned Vehicle Systems International (AUVSI) Foundation [2]. These types of competition give an enormous contribution to the next generation technologies. ASV has been developed for ocean observation can work under rough ocean and observe the environment on coastal beaches, oil polluting sampling in harbor basin [3]. Over the past decades several ASV similar to catamaran, like autonomous modular unit (SEASAMO), Charlie, ROAZ and delfim; has been developed and used to study the sea-air interference and sampling the sea surface [4]. Fig 1. Shows the famous catamaran boats developed in recent years.

1. Autonomous catamaran Delfim was developed for the purpose of automatic marine data acquisition and as a communication relay for companion AUV in Lisbon 2000 [5]
2. Autonomous catamaran Charlie was developed for the collection of the sea surface microlayer and then upgraded for robotic research by CNR-ISSIA Genova 2005 [6].

Fig. 1. Famous Catamaran shape Boats.

3. Autonomous catamaran ROAZ was developed to support AUV missions and multiple operations with ISEP-Institute of engineering of Porto in Potugal 2006 [7].
4. Autonomous catamaran Springer was developed to track and monitor water pollutants and geographical survey by University of Plymouth, U.K 2006 [8].

The WAM-V is a catamaran type of vehicle and the behavior of the vehicle is different from a conventional ship. Interference resistance acts because of cross-flow effects and this have been studied for catamaran (series-60) theoretically and experimentally under different conditions [9]. Interference resistance theories were proposed to study the effects of multihull interference [10]. The WAM-V is a high speed marine vehicle. The unique aspects of High Speed Vehicles such as resistance, propulsion, seakeeping and maneuvering are extensively defined in the literature [11]. Applications of hydrodynamics and empirical design information are illustrated [12]. This research addresses the problem of heading control of WAM-V. This paper describes the design and simulation results of a WAM-V ASV robot, built for taking various missions in the ocean environment. The design of WAM-V, including embedded systems, sensors, and mathematical modeling for deriving Nomoto's system response model has been described. For precise mathematical modeling of the system dynamics, hydrodynamics coefficients of the WAM-V hull are divided from model basin test facility at Osaka University. Finally, the simulation results for PID tracking control, using WAM-V system mathematics are also described.

II. Configuration of WAM-V

Wave Adaptive Modular Vessel (WAM-V) is an entirely new class of vessels. There are several modified designs like Proteus was the first generation design and then two 12' and a 33' Wam-V was the second and third generation respectively [13]. It has been designed to adapt to the shape of water surface. WAM-V is equipped with springs, shock absorbers, and ball joints giving enough agility to the vessel and damping stresses to structure and payload as shown in Fig. 2. Two propellers attached to the aft part of each pontoons with special hinges that keep the propeller in the water all the times. High frequency waves are absorbed by the air filled pontoons. The 2:1 length-to-beam ratio, in addition to ball joint and suspension system, makes the WAM-V a stable platform. The main physical dimension of WAM-V used in this study is shown in Table.I.

Fig. 2. WAM-V Catamaran robot.

III. Mathematical Model of WAM-V Catamaran Boat

A successful control system design requires knowledge of the system to be controlled. This knowledge is captured by mathematical model such as MMG model [14], [15] and Nomotos's model [16]. For aquatic applications WAM-V movement can be described by 3-degrees of freedom which lies in the plane parallel to the surface of the water, namely surge, sway and yaw as shown in Fig. 3

TABLE I: FEATURES OF WAM-V

Parameters	***Measurements***
Hull Length	3.91 m.
Hull Diameter	4.2.6 m.
Overall Vehicle Height	1.27 m.
Overall Vehicle Width	2.44 m.
Payload	136 Kg. (Maximum)
Full Load Displacement	255 Kg.
Draft	0.165 m.
Primary Sensors	GPS, Camera, LRF, INS, Hydrophone- Pinger
Parameters	Measurements

At this point the vehicle position and orientation are described by the vector R=[x y ψ], while the vehicle state vector is s= [u v r]. It is based upon the fact that the robo-boat moves in a plane parallel to the surface of water and turn only z-direction. The propelling and turning manoeuvre of WAM-V can be controlled by the two turnable propellers installed on each hull. The non-linear dynamic equation can be expressed in vector form as given in equation (1) [17].

$$M\dot{\vec{v}}+C\left(\vec{v}\right)\vec{v}+D\left(\vec{v}\right)\vec{v}+G\left(\vec{\eta}\right)=\vec{\tau} \qquad (1)$$

Where M is the inertial matrix (including added mass), $C(\vec{v})$ is the Centripetal and Coriolis acceleration, $D(\vec{v})$ is the hydrodynamic damping matrix, $G(\vec{\eta})$ is the restoring force and moments matrix, and $\vec{\tau}=[X,Y,Z,K,M,N]^T$ represents the resultant forces and moment matrix.

$$\begin{Bmatrix} X \\ Y \\ N \end{Bmatrix} = f\left\{u,v,\dot{u},\dot{v},r,\dot{r},n\right\} \qquad (2)$$

Based on the method of MMG [14], [15], we can separately analyze the outside force and control force on the WAM-V, the equations of motions are shown in equation (3).

$$\begin{aligned}
&\left(m+m_x\right)\dot{u}-\left(m+m_y\right)rv = X_H + X_P \\
&\left(m+m_y\right)\dot{v}+\left(m+m_x\right)rv = Y_H + Y_P \\
&\left(I_Z+J_Z\right)\dot{r} = N_H + N_P
\end{aligned} \qquad (3)$$

Where X_H, Y_H and N_H are the heading force, sideslipping force and yawing torque, which are caused by others, such as wind, wave, current and X_P, Y_P, N_P are the forces caused by WAM-V turnable propellers. m_x and m_y are the added mass on x & y directions. I_Z and J_Z Are the rotational inertia and added rotational inertia in x and z directions. Then u is heading, speed, v is sideslipping speed and r is the yawing angular velocity.

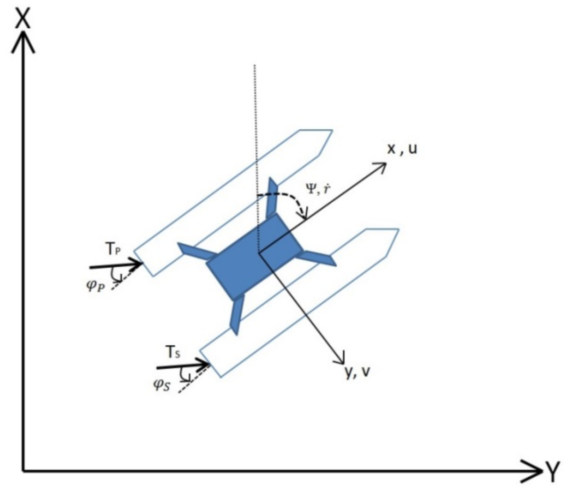


Fig. 3 Coordinate system of WAM-V.

When the WAM-V motion parameters u, v and r is very small, the variables higher than second order can be omitted and the derivative of the forces and moments respect to a given variable indicates the change in the fluid forces and moments when the given variables are changed slightly from the equilibrium value, with all other variables remaining at their equilibrium value. Hydrodynamic variables are calculated with the help of captive model test of WAM-V. The equation can be rewritten as the linear motion equation (4), (5) & (6).

$$\left(m+m_x\right)\dot{u} = X_u u + X_P \qquad (4)$$

$$\left(m+m_y\right)\dot{v}+\left(m+m_x\right)ur = Y_v v + Y_r r + Y_P \qquad (5)$$

$$\left(I_Z+J_Z\right)\dot{r} = N_v v + N_r r + N_P \qquad (6)$$

The motion of WAM-V is controlled by the revolution speed np and ns and the angles $\varphi_{(P)}$ and $\varphi_{(S)}$ of the two turnable propellers installed on the two hulls at the x_g distance from center of gravity G. The subscript (P) and (S) are defined as the port and starboard propeller, the distance between the propellers action points and the baseline are $Y_{(p)}$ and $Y_{(s)}$ as described by the Fig .4.

A. Propulsion System Modelling

The thrust exerted by each propeller can be modeled as (7)

$$T = a_n n\left|n\right| = a_v V\left|V\right| \qquad (7)$$

Where V is the reference voltage applied to servo-amplifiers and n is the propeller revolution rate. V is proportional due to servo amplifier section. $k_{T(P)}$ and $k_{T(S)}$ are the thrust coefficients of the propellers. As the $\varphi_{(P)}$ and $\varphi_{(S)}$

are the turnable angles so the component of propulsion forces acting on the all three degrees of freedom shown in equation (8).

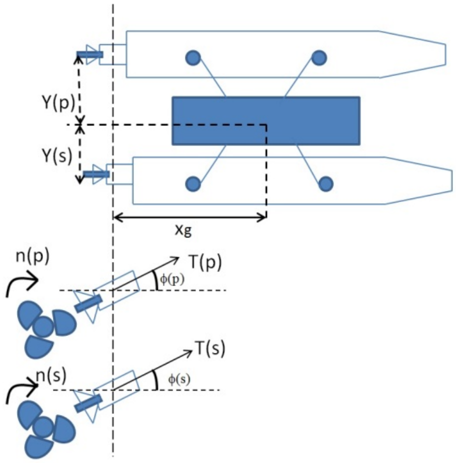


Fig. 4 The Turning propeller arrangement diagram

$$
\begin{aligned}
X_P &= X_{(S)} + X_{(P)} = (1-t_P)(T_{(S)}\cos\varphi_{(S)} + T_{(P)}\cos\varphi_{(P)}) \\
Y_P &= Y_{(S)} + Y_{(P)} = (1-d_{YP})(T_{(S)}\sin\varphi_{(S)} + T_{(P)}\sin\varphi_{(P)}) \\
N_P &= N_{(S)} + N_{(P)} \\
&= (1-d_{NP})(T_{(S)}(Y_{(p)}\cos\varphi_{(S)} + x_{(G)}\sin\varphi_{(S)})) \\
&+(T_{(P)}(-Y_{(p)}\cos\varphi_{(P)} + x_{(G)}\sin\varphi_{(P)}))
\end{aligned} \tag{8}
$$

Where t_P is the thrust deduction factor generated by the propeller in x-direction. The value taken here is 25%. d_{YP} and d_{NP} are the propeller influence factor to the Y and N directions. In case of fix propeller system $\varphi_{(P)} = \varphi_{(S)} = 0$. There is no propeller force in Y direction so X_P and N_P expressions are shown in equation (9).

$$
\begin{aligned}
X_P &= (1-t_P)(T_{(S)} + T_{(P)}) \\
N_P &= (1-d_{NP})(T_{(S)} - T_{(P)})y_P
\end{aligned} \tag{9}
$$

So basically in this case when the revolution speed of the two propellers on the portside and starboardside are different, generate turning moment and produce the same effect as a rudder. By eliminating v in equation (5) and (6), and after making it non-dimensionalized the yawing response equation of WAM-V is achieved (10),(11),(12),(13),(14),(15) &(16).

$$q1\times\dddot{r}' + q2\times\ddot{r}' + q3\times r' = q4\times P + q5\times\dot{P}' \tag{10}$$

$$q1 = (m' + m_y')\times(I_Z' + J_Z') \tag{11}$$

$$q2 = -Y_V(I_Z' + J_Z') - N_r'(m' + m_y') \tag{12}$$

$$q3 = Y_V{}' N_r' - N_V'(Y_r' - m') \tag{13}$$

$$q4 = N_V' Y_P{}' - N_P' Y_V{}' \tag{14}$$

$$q5 = (m' + m_y')N_P{}' \tag{15}$$

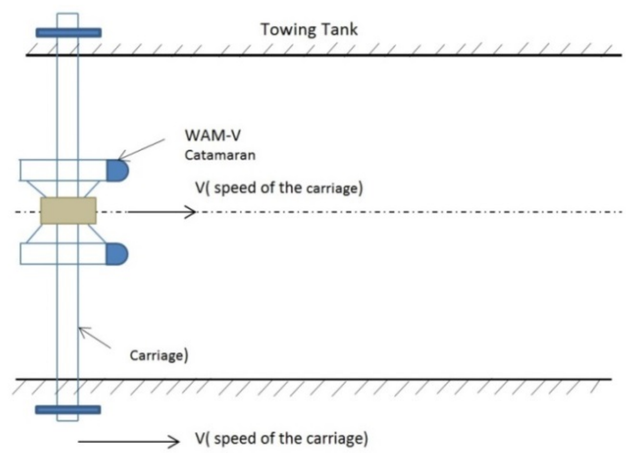
$$T_1'T_2' = \frac{q1}{q2}; (T_1' + T_2') = \frac{q2}{q3}; K_p = \frac{q4}{q3}; T_3' = \frac{q5}{q4} \tag{16}$$

$$T_1'T_2'\ddot{r} + (T_1' + T_2')\dot{r} + r = K_p{}'T_3'\dot{P}' + K_p{}'P' \tag{17}$$

Equation (17) coincides with the WAM-V's movement response equation controlled by the traditional rudder and can be regarded as the extension of the famous 2nd order K-T equation proposed by Nomoto on the ship which integrates the propeller and the rudder as a whole. The difference between a traditional movement response equation is that the manoeuvre control variable is generated by the force caused by the propeller revolution per second (R.P.S) difference between port and starboard not the rudder.

IV. Method for Determining the Hydrodynamic Forces Acting on a Manoeuvring Ship

A precondition to use the equations of motion to simulate the maneuvering motion, the hydrodynamic derivatives in the equation should be determined [18]. In our analysis captive model test were conducted with WAM-V catamaran including double and single hull which can be used to determine the hydrodynamic force and moment acting on a WAM-V in manoeuvring motion. The captive model test was conducted in Osaka University Towing tank facility Fig. 5.

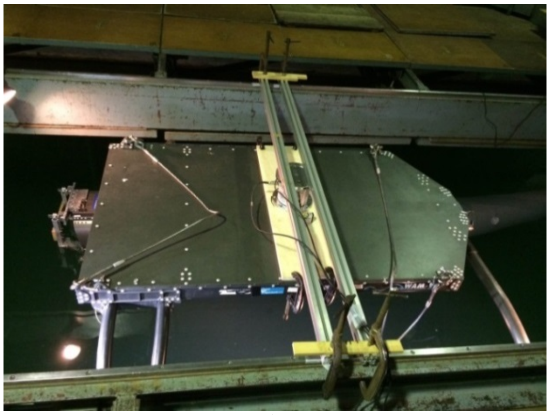


(a)

A. Resistance Force

The resistance curves for the monohull and the catamaran are presented for 0.0<fn<0.45 in Fig 6. for pointing out that monohull resistance has been doubled for the comparison. The presence of multihulls generates cross flow effects.

It can be observed from the experimental curve that at higher velocities (fn>0.3) interference effect between the catamaran is smaller than twice of that of the monohull. Interference factor is calculated with the help of formula [9] as "-0.1" but it is very small and ideally the value should be kept small as possible, negative if achievable [10].



(b)

Fig. 5 Towing Tank Experiments (a). Graphical representation of the setup. (b). Experimental representation of the setup.

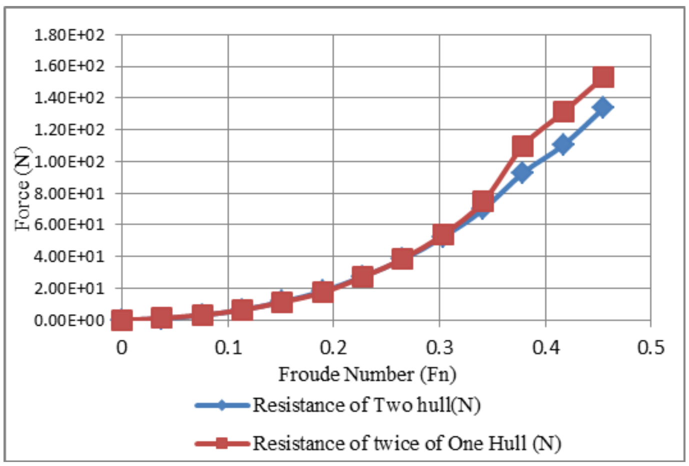
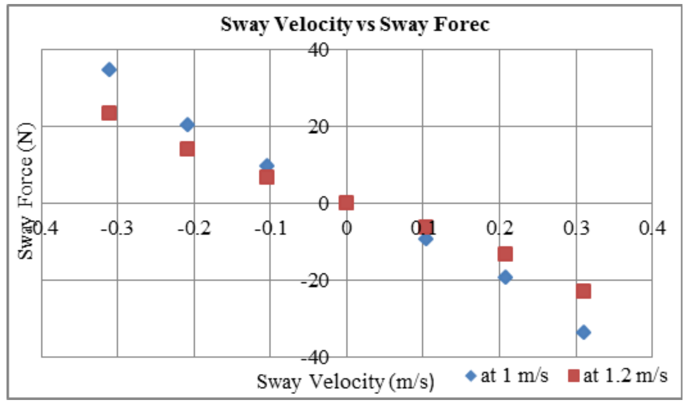


Fig. 6. Resistance curve of Two Hull and Twice on one Hull of WAM-V

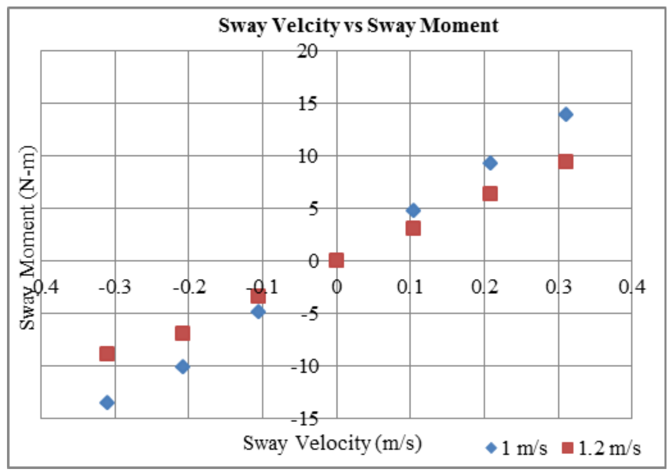
B. *Linear hydrodynamic derivatives*

In this paper the calculation of hydrodynamic derivatives is presented experimental as well as calculated with the help of empirical and semi empirical expressions for conventional ship and analyzed. From towing tank experiments the force and moment induced by a unit component of velocity or acceleration in maneuvering motion, while the other components keep vanished is calculated. The gradient of the curve of force or moment versus velocity given the value of linear hydrodynamic derivatives as seen from the graph as shown in Fig. 7 (a) & 7 (b). The graph shown below shows sway force /moment versus velocity at 1 m/s and 1.2 m/s achieved by changing the drift angle as -15, -10, -5, 0, +5, +10 and +15 degrees. There is some difference found because of the change of the lift force generated at two different velocities 1 and 1.2 m/s.

The non dimensionalized design ratios for WAM-V are calculated in order to calculate the hydrodynamic parameters using empirical relationships (e.g. Inoue's Formula) exists in the literature for conventional ship.



(a)



(b)

Fig. 7 (a). Graph between Sway velocity and Sway force (at 1 m/s & 1.2 m/s), (b). Graph between Sway velocity and Sway moment (at 1 m/s & 1.2 m/s).

Graph 7(a) and 7(b) are obtained from captive model test of WAM-V and with help of least square method the hydrodynamic damping derivatives are calculated.

The WAM-V is neither similar to conventional ship nor like a catamaran boat so it was decided to calculate with the help of the captive model experiment. The non dimensionalized design ratios for WAM-V is tabulated in Table II.

TABLE II. NON DIMENSIONAL MAIN PARTICULARS

Description	***Symbol***	***Magnitude***
Block Coefficient	Cb	0.55
Water Plane Area Coefficient	Cwa	0.71
Prismatic Coefficient	Cpa	0.59

The virtual masses and virtual moment of inertia which are typical terms seen in ship motions are calculated with the help of Motora's chart [19] as given in the Table III.

TABLE III. NON DIMENSIONAL MAIN PARTICULARS

Description	*Symbol*	*Magnitude (non-dimensional)*10e-2*
Mass of the WAM-V	m'	2.20
Added Mass on x-axis	mx'	0.02
Added Mass on y-axis	my'	765
Rotational Inertia	Iz'	553
Added Rotaional Inertia	Jz'	0.04

The higher order coefficients are neglected. First order terms are given in Table IV.

TABLE IV. HYDRODYNAMIC DERIVATIVES OF WAM-V

Hydrodynamic Derivatives	*Magnitude (non-dimensional) *10e-2*
Yv'	-2.06
Nv'	-0.86
Yr'	0.065
Nr'	-0.351

V. PID TRACKING CONTROLLER DESIGN OF THE WAM-V'S PROPELLING AND TURNING MANOEUVRE

The Autopilot is a controller that regulates the heading to a desired value provided by the guidance system [18], [20]. To check the basic automatic maneuvering and guidance capabilities, auto heading proved to be sufficient for the scientific end user for marine application. When WAM-V is sailing at given speed and a given heading, turning of the propellers an cause the effect of a rudder. When the revolution speed of the two propellers on the port and starboard are different than three conditions can be generated

$$\left(n_p \sim n_s\right) = 0 \ \text{Straight Line}$$

$$\left(n_p \sim n_s\right) > 0 \ \text{Clockwise Turning}$$

$$\left(n_p \sim n_s\right) < 0 \ \text{Anticlockwise Turning}$$

A conventional PID tracking controller of the WAM-V heading has been designed. 2nd order mass spring damper system is taken as a reference system which helps to tune the control parameters. The output variables are the reference and estimated heading ψ and ψ_d. PID control law is defined by the Eqn. 18 and Simulate in Simulink as Fig. 8.

$$\tau_{PID} = K_p\left(\psi_d - \psi\right) - K_d\left(r_d - r\right) + K_i \int_0^t \left(\psi_d - \psi\right) d\tilde{\psi} \tag{18}$$

Where proportional gain $\left(K_P\right)$,Integral gain and $\left(K_i\right)$ derivative gain $\left(K_d\right)$ are the regulator design parameters.

The control system provides the necessary feedback signal to track the desired yaw angle ψ_d .The output is the yaw moment τ_{PID} . This system processes information to infer the state of the WAM-V plant and to generate an appropriate command for the actuators so as to reduce the reference heading and actual heading.

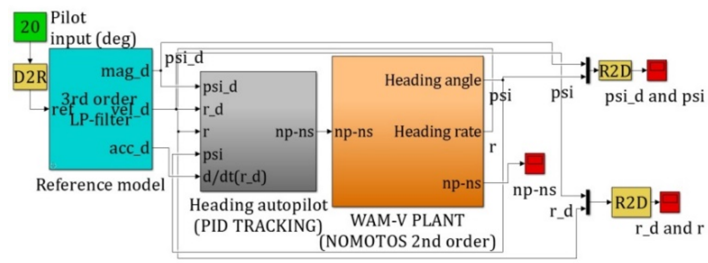
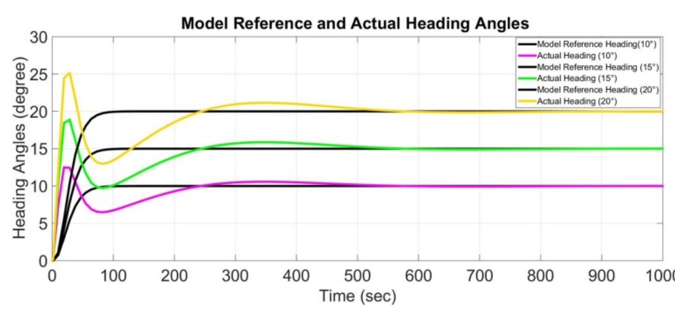
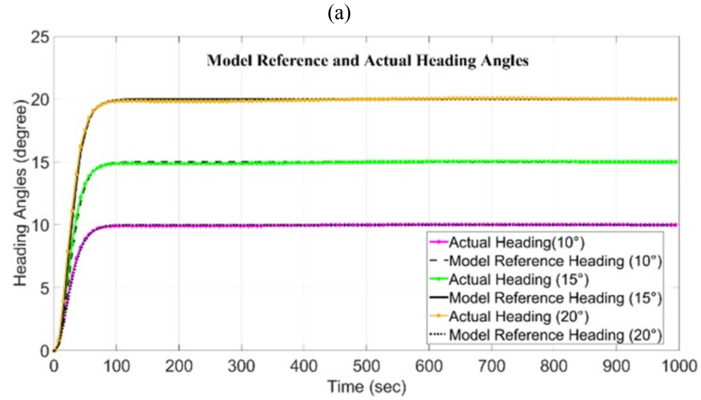


Fig. 8. Simulink Model of Control System

Without proper tuning of proportional gain $\left(K_P\right)$,Integral gain $\left(K_i\right)$ and derivative gain $\left(K_d\right)$ there is an overshot as shown in graph Fig 9. (a) and after tuning $K_p = 0.18, K_i = 0.001$ and $K_d = 0.33$. The results are shown in Fig 9. (b).



(a)



(b)

Fig. 9. Graphs of Heading angles changing with time (a). Without tuning system parameters (b). After tuning system parameters

VI. CONCLUSION:

WAM-V Catamaran robots have relevant applications in numerous fields like coastal surveillance and protection, environmental monitoring, automated bathymetry survey, military applications and support for Autonomous underwater vehicles (AUV's). The continued development of WAM-V has also brought about the new complex mission that the vehicle must perform. New generation catamarans would free from several problems such as controlling the vehicle, so that it can operate autonomously, gathering the sensor information and passing the information in real time. In this paper measured data of captive model test conducted with single hull and full WAM-V were presented. The use of experiment has recently enabled significant advances to be made in the understanding of high speed craft performance at sea. The Measured data were analyzed on the basis of the motion equations together with the WAM-V mathematical model including hydrodynamic coefficient. Interference resistance, including two hull and single hull was studied. Second order Nomoto's model was derived from WAM-V system of motion equation. Using the Nomoto's system model along with model reference heading generator was used to tune PID heading controller parameters. The effect of tuned PID parameter and untuned PID parameter on heading response of WAM-V was studied. From the simulation results PID heading controller with tuned parameter was found effective in controlling the vessel heading based upon the reference heading generated by model reference heading. Control Design for high speed autonomous vehicles such as WAM-V is challenging due to uncertainty in dynamic models, significant sea disturbances, underactuated dynamics and overestimated or underestimated of hydrodynamic parameters. Future work includes conducting free running model test to know the behaviour of the WAM-V more accurately. More robust control techniques will be applied to improve the autonomous behaviour of the system. We believe that tremendous opportunity exists for modular and customized WAM- V.

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