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Study on Turning Manoeuvre of Catamaran Surface Vessel with a Combined Experimental and Simulation Method

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Abstract: In this paper a wave adaptive modular vessel (WAM-V) catamaran vessel is introduced with its manoeuvring performances in calm and deep water. The main structure and concept of WAM-V free running model ship is introduced. The manoeuvring mathematical model group (MMG) mathematical model encompassing calm water maneuver is developed to simulate the turning circle test of WAM-V. The straight line and turning manoeuvring tests are conducted at the experiment pond facility, Osaka University. The turning characteristics of catamaran WAM-V with differential thrust conditions are studied and experimental results are compared with the simulation results. Manoeuvring derivatives in the equations of motion are determined with the help of the captive model test and certain parameters of the hydrodynamic force, which could not be determined from the captive model tests, are estimated by means of the parameter identification method. A dynamic thrust characteristics are studied for port and starboard side turning. A notable phenomenon is identified lack of port and starboard symmetry of side forces of the propellers. The MMG mathematical model developed here is successful in simulation the turning circle with differential thrust and comparable with experimental results.

Keywords: Maneuverability of Catamaran, MMG Mathematical Model, Turning Characteristics, Differential Thrust, Free Running Trials, Wave Adaptive Modular Vessel (WAM-V)

1. INTRODUCTION

The knowledge of the maneuvering capabilities of ships has already been required to control the vessel for various marine applications. Various international organizations like IMO (International Maritime Organization), ITTC (International Towing Tank Conference) and SNAME (Society of Naval Architecture and Marine Engineering) have developed to give recommendations about the test and assess the maneuverability and performance of the ship. Free running model tests are often preferred because they confirm manoeuvring properties of a ship configuration in the most direct and convincing way. The method of computer simulation using mathematical models becomes more and more popular due to rapid development of the computer technology. The mathematical model for ship manoeuverability is the most important issue for a ship manoeuvring simulation. Apparently by the end of 1970's, it appeared that there were many manoeuvring mathematical models was established, but it was necessary to develop a model for new types of ship. The MMG mathematical model was proposed (1977) by a research group called Manoeuvring Modelling Group in Japanese Towing Tank Conference (JTTC), and the outlines was reported in the bulletin of Society of Naval Architects of Japan. Ogawa et al. (1980) described the concrete methods of MMG model, including hydrodynamic forces acting on the ship. Yoshimura et al. (2015) revised full model with adding some interaction coefficient in the model. Fang, et al. (2005) showed a simplified 6 DOF mathematical model for ship turning circle is simulated to predict the manoeuvrability of a ship in regular waves. The self-propelled model is composed with the motion sensors (GPS, GYRO etc.), thrusters, communication module, batteries and computers. Measurements are generally made with respect to the motion trajectories and the ship velocity, heading angle, yaw rate, etc. Surprisingly, studies on catamaran manoeuvring are not very diverse. There is continued interest for high speed vessels used for recreational, racing, transportation and etc. purposes. Owing to their speed and performance, the number of planning hull has increased. Zlatev et al. (2009) studied EFD and CFD based manoeuvring characteristics of Delf catamaran and validated the results. Im et al. (2010) studied maneuvering performance of 3m. free running model ship and presented the experimental results. Stern et al. (2011) has shown good results for manoeuvring using MMG model. Moreira et al. (2011) performed the manoeuvring tests autonomously, the system was developed and implemented in a model of the Esso Osaka ship. Hornaryar et al. (2014) presented combined numerical and experimental method to determine the damping force and moment coefficients of a catamaran boat in calm water. A WAM-V is a high speed marine craft with tremendous control and maneuverability in tight, giving its advantage over the other Autonomus Surface Vessel (ASV). It has caught the attention of the scientific community due to its unparalleled advantages, in the recent year, a series of applications oriented such as 3D mapping of the port area and oceanographic mission related projects have been carried out wing of the WAM-V platform. The WAM-V is still under development and lots of work is being carried out in dynamic modeling and other areas to understand the dynamic behaviour of the vessel. In this open loop-trial, a self propelled WAM-V is steered by radio control on the water by giving some control commands and motion trajectories. Time histories of motion variables, etc. are measured. In this test, the WAM-V is stable in motion so there is no unstable coupled heave and pitch motion. The open water trial is required to characterize a WAM-V maneuverability and dynamics. The remainder of this paper is organized as follows: in the section 2. Configuration of WAM-V for free running model experiments are described. In section 3 MMG mathematical model with hydrodynamic parameters of WAM-V are defined. In section 4. The thrust calculation procedure is discussed, including speed tests and turning circle tests are briefly discussed. In section 5. Conclusions and future work are discussed.

2. THE CONFIGURATION OF WAM-V FOR FREE RUNNING MODEL EXPERIMENT

Marine advanced research, Inc. (2011) launched the new generation vessel named WAM-V. It has been designed to adapt to the shape of the water surface. WAM-V is equipped with springs, shock absorbers, and ball joints which give enough agility to the vessel and damping stresses to the structure and payload as shown in fig. 1. 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.

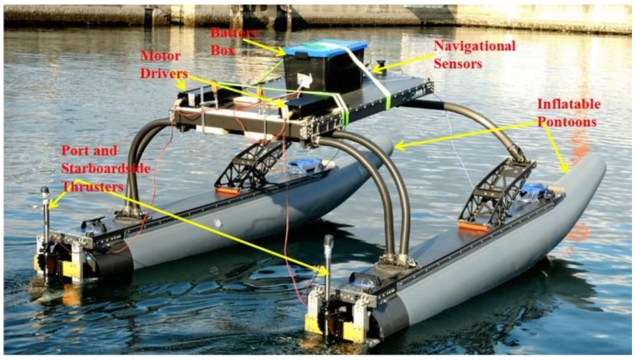

Fig. 1. WAM-V Catamaran robot

The vehicle features a global positioning system receiver and gyro sensor. Using the GPS satellite constellation, it provides the system with an estimate of its latitude and longitude. Those values are used to calculate X and Y position of the vehicle. The propulsion system of the vehicle consists of a pair of Minn. Kota transom mount trolling motors. The operating system is operated by inner computer on board which is controlled from shore computer via wireless network communication

The main physical dimension of WAM-V used in this study is shown in Table.1.

Table 1. Main Particulars of WAM-V

Parameters	*Measurements*
Hull Length	3.91 m.
Hull Diameter	4.26 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

Fig. 2 shows the navigation layout for the free running experiments.

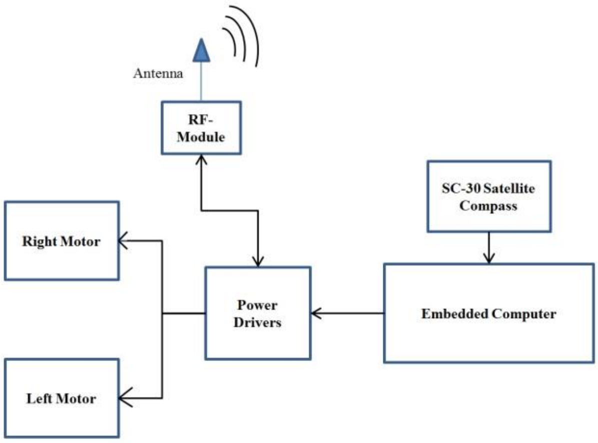

Fig. 2. WAM-V Navigation System Layout

3. MATHEMATICAL MODEL AND MANOEUVRING DERIVATIVES

Numerous methods were proposed to predict and reproduce the ship manoeuvrablibity during the long history of ship dynamics research. First, the motion equation to express the manoeuvring motions for a WAM-V with twin hull-twin propeller and the simulation model of hydrodynamic forces acting on the WAM-V is described. 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. The z-axis is chosen so as to be perpendicular to the xy-plane (positive upward). Fig. 3 shows the coordinate system of WAM-V.

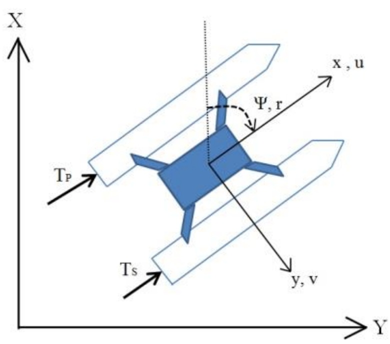

Fig. 3. Coordinate system of WAM-V.

The MMG- type modular maneuvering model has been found to be suitable for investigation, such a vessel's maneuvering characteristics of two propeller vessel. The model consists of a hull, propeller and rudder characteristics with their interaction effect. Based on the method of MMG, we can separately analyze the outside force and control force on the WAM-V, the equations of motions is calculated by (1).

$$(m + X_{\dot{u}})\dot{u} - (m + Y_{\dot{v}})rv = X_H + X_P$$
$$(m + Y_{\dot{v}})\dot{v} + (m + X_{\dot{u}})ur = Y_H + Y_P \qquad (1)$$
$$(I_Z + N_{\dot{r}})\dot{r} = N_H + N_P$$

Where (u, v, r) are vehicle's surge velocity, sway velocity and yaw rate respective, m is the vehicle's mass and I_Z is the moment of inertia about the Z axis. X_H, Y_H and N_H are the hydrodynamic forces acting on the hull. X_P, Y_P and N_P are the forces caused by WAM-V propellers. As there is no rudder, so rudder forces are zero. After expanding the above equation and putting the value of hull forces the (2) is achieved. The variables higher order terms are 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. The external disturbances are not considered in the simulation.

$$m(\dot{u} - vr) = X_{\dot{u}}\dot{u} + X_{vv}v^2 + X_u(U) + X_P$$
$$m(\dot{v} + ur) = Y_{\dot{v}}\dot{v} + Y_{\dot{r}}\dot{r} + Y_v v + (Y_r + X_{\dot{u}}u)r + Y_{vvv}v^3 \qquad (2)$$
$$I_Z\dot{r} = N_{\dot{v}}\dot{v} + N_{\dot{r}}\dot{r} + N_v v + N_r r + N_{vvv}v^3 + N_P$$

WAM-V is an underactuated vessel with control forces and moments acting only in the surge and yaw DOF. The WAM-V relies on differential thrust for steering. So basically in this case when the thrust of two propellers on the portside and starboardside are different, generate turning moment and produce the same effect as a rudder. Where T_P and T_S denote the thrust from the port and starboard propellers, respectively. t_P is the thrust deduction factor and the value taken here is 0.25, d_{NP} is the propeller influence factor is taken here is 25% and y_P is the separation distance between the centerline of each hull. There is no propeller force generated in the Y- direction. Propeller force is X- direction and turning moment in Z direction are calculated by (3).

$$X_P = (1 - t_P)(T_S + T_P)$$
$$N_P = (1 + d_{NP})(T_S - T_P)y_P \qquad (3)$$

To simulate the manoeuvring motion, the Manoeuvring derivatives in the equation should be determined. Using these all the equations the dynamic simulation of the vehicle is created. Faltinsen (2005) performed his research on catamaran vessel and found that determining the hydrodynamic coefficients with the use of purely theoretical methods to predict the ship maneuverability is still underdeveloped. Although Inoue et al. (1981) derived some semiempirical formulae to calculate the Manoeuvring derivatives of conventional ships. Motora (1959 and 1960) provided an empirical method for estimating the added masses and added moment of inertia from model tests with various conventional ships, which is known as motora's chart. The WAM-V is neither similar to conventional ship nor like a catamaran boat so it doesn't satisfy the assumptions to use those formula's. So it is decided to calculate the Manoeuvring derivatives of WAM-V with the help of the captive model experiments. Pandey et al. (2015) conducted a captive model test in the Osaka University towing tank and calculated some hydrodynamic parameters for WAM-V which is used in this research. Certain parameters such as $Y_r, N_r, X_{\dot{u}}, Y_{\dot{r}}, N_{\dot{V}}$ and $N_{\dot{r}}$ which could not be determined from the captive model tests are estimated by means of the parameter identification methods. Parameter identification can predict or tune the system parameters in the mathematical model of a dynamic system from measured data of free running experiments. Non-dimensional coefficients are defined as

$$X_{\dot{u}}' = \frac{X_{\dot{u}}}{\frac{1}{2}\rho L^2 d};\; Y_{\dot{v}}' = \frac{Y_{\dot{v}}}{\frac{1}{2}\rho L^2 d};\; N_{\dot{v}}' = \frac{N_{\dot{v}}}{\frac{1}{2}\rho L^3 d}$$

$$X_{vv}' = \frac{X_{vv}}{\frac{1}{2}\rho L d};\; Y_{\dot{r}}' = \frac{Y_{\dot{r}}}{\frac{1}{2}\rho L^3 d};\; N_{\dot{r}}' = \frac{N_{\dot{r}}}{\frac{1}{2}\rho L^4 d};$$

$$Y_v' = \frac{Y_v}{\frac{1}{2}\rho L d U};\; N_v' = \frac{N_v}{\frac{1}{2}\rho L^2 d U};\; Y_r' = \frac{Y_r}{\frac{1}{2}\rho L^2 d U}$$

$$N_r' = \frac{N_r}{\frac{1}{2}\rho L^3 d U};\; Y_{vvv}' = \frac{Y_{vvv}}{\frac{\rho L d}{2U}};\; N_{vvv}' = \frac{N_{vvv}}{\frac{\rho L^2 d}{2U}}$$

The non dimensionalized design ratios for WAM-V is tabulated in Table 2.

Table 2. Manoeuvring derivatives of WAM-V

Manoeuvring derivatives	Magnitude (non-dimensional) *10e-3
$X_{\dot{u}}'$	-830
X_{vv}'	-880
$Y_{\dot{v}}'$	-1120
$Y_{\dot{r}}'$	-435
Y_v'	-1155
Y_r'	-500
Y_{vvv}'	-0.80

$N_{\dot{v}}'$	25
$N_{\dot{r}}'$	-89
N_{v}'	-265
N_{r}'	-177
N_{vvv}'	1659

4. MANOEUVRABILITY TESTS

This kind of tests is the most direct method for predicting the manoeuvring performance. The standard manoeuvers are performed and the parameters evaluating manoeuvring characteristics are measured directly from the test record. In this manoevrability test the user inputs are the voltage signal send to each propeller. Fig. 4 shows the four possibilities for the propeller rotation.

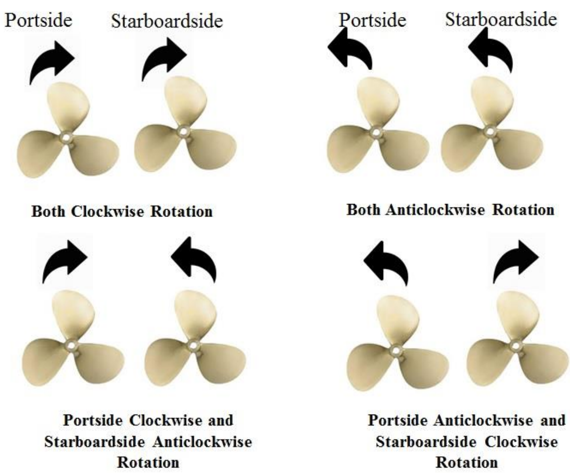

Fig. 4. Combinations of propeller rotation

Different voltage input generates different thrust. With these 4 propeller rotation directions there may be several combinations are possible for turning test. So it is decided to check it at some specific values as listed in table 3.

Table 3. Notations of control panel

Notation	Voltage (V)	Rotation Direction	Notation	Value	Rotation Direction
A	0	Anticlockwise	a	0	Clockwise
B	2.4	Anticlockwise	b	2.4	Clockwise
C	4.8	Anticlockwise	c	4.8	Clockwise
D	7.2	Anticlockwise	d	7.2	Clockwise
E	9.6	Anticlockwise	e	9.6	Clockwise
F	12	Anticlockwise	f	12	Clockwise

In simulation model the anticlockwise rotation of propeller is taken as positive and clockwise as negative.

4.1 Thrust Measurement

For an underactuated system, there is only one solution to the thrust allocation problem. Only one possible state of the actuator exists in order to achieve the desired state. Adequate manoeuvrability can be achieved through linear motion and rotations. The forward motion is achieved with equal efforts from each thruster, while rotation requires a difference in thrust. In this research the thrust generated by the propellers is calculated indirectly. The control is applied to the actuators in the form of the pulse width modulation (PWM) duty cycle to drive the motor. Hence the motor would be driven at up to the maximum voltage (12 V to 100% duty cycle). Pandey et al. (2015) also calculated the resistance of WAM-V at a different vessel velocity is measured with the help of the captive model test. With the help of free running model test relation between the voltage supplied to the thrusters and vessel velocity is measured. With these two tests the dynamic thrust generated by the propellers with the supplied voltage can be estimated for portside and staboardside turning. Fig. 5 shows the vessel resistance force versus vessel velocity and supplied voltage versus vessel velocity.

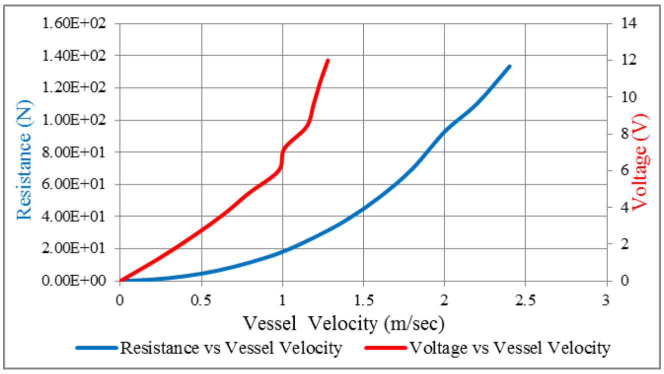

Fig. 5. Resistance and voltage Vs vessel velocity

In this WAM-V free running experiments both the propellers have the same pitch. In this configuration considerable influence on the side force is observed. In this propeller configuration of the port and starboardside force is almost asymmetrical. The effect of the port and starboard thrusters should cancel each other, but here the portside turning and starboardside turning are different due to inflow velocity. In a shallow water, it is found that the maximum force to the starboardside is almost 35% greater than portside. The lateral thrust added on the starboard side so the turning circle on starboard side is smaller that the portside.

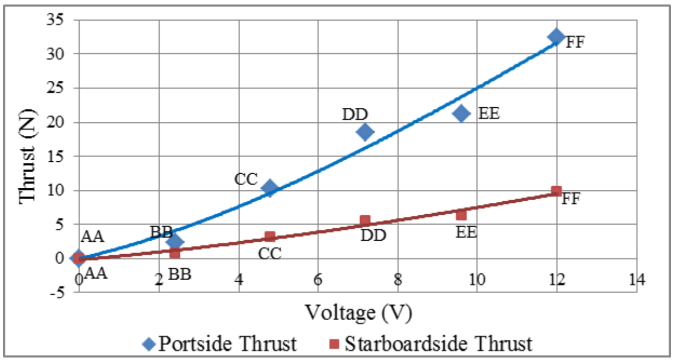

Fig. 6. Portside and Starboardside thrust Vs voltage graph

In simulation these observations are incorporated using equation 3. All the simulation including graphical user interface is designed in Matlab/Simulink. Fig. 6 shows the port and starboardside dynamic thrust with the input voltage.

4.2 Speed Test

Speed tests are performed with the goal of identifying the relation between vehicle speed and voltage supplied. The GPS location and heading is recorded with the help of sensors. Open loop type of test is not typically expected to be stable because of the inherent nonlinearity of the system and this is why with the open loop speed commands the vehicle's track is unstable and doesn't naturally follow the track. In this test the same voltage is supplied to each propeller at the same time. Fig. 7 shows the experimental and simulation results with respect to the velocity of WAM-V at different voltage supply.

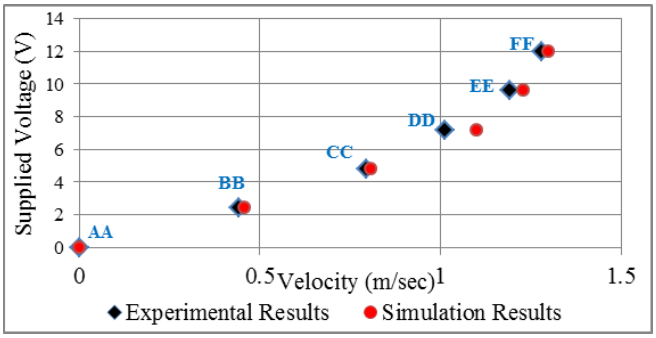

Fig. 7. Experimental and Simulation results of speed test

4.3 Turning Test

Thruster rotation speed governs the motion trajectory of the WAM-V. A differential thrust force can be generated by controlling the voltage of the individual thruster for applying a turning moment to turn the WAM-V in the required direction.

Due to same pitch propellers used in port and starboard side, there is some discrepancy in portside and starboardside turning. The turning ability of WAM-V greatly varies depending on the approach speed that is caused by speed effects on the hull forces. In this experiment the wind condition was not measured. Fig 8 shows the simulation result of rate of turn at different turning test.

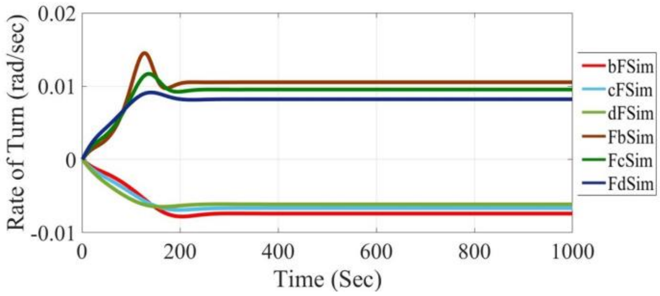

Fig. 8. Simulation results of rate of turn at different turning tests

Hence, the controlled voltage of port and starboardside thruster can produce similar manoeuvering forces as that of conventional rudder. In the turning test experiment for WAM-V, port and the starboard thruster are rotated at different voltage input and the notations are defined in table 2. During the experiment the GPS data was stored and analyzed offline to see the turning response of the WAM-V, with the change in rotational speed of the port and starboard thruster. The left hand side and right hand side trajectories of experiment results may have some effect of different wind conditions, but in simulation wind conditions are not incorporated. Fig. 9 shows the comparison of simulation and experimental results of portside and starboardside turning of WAM-V at different input thrusts.

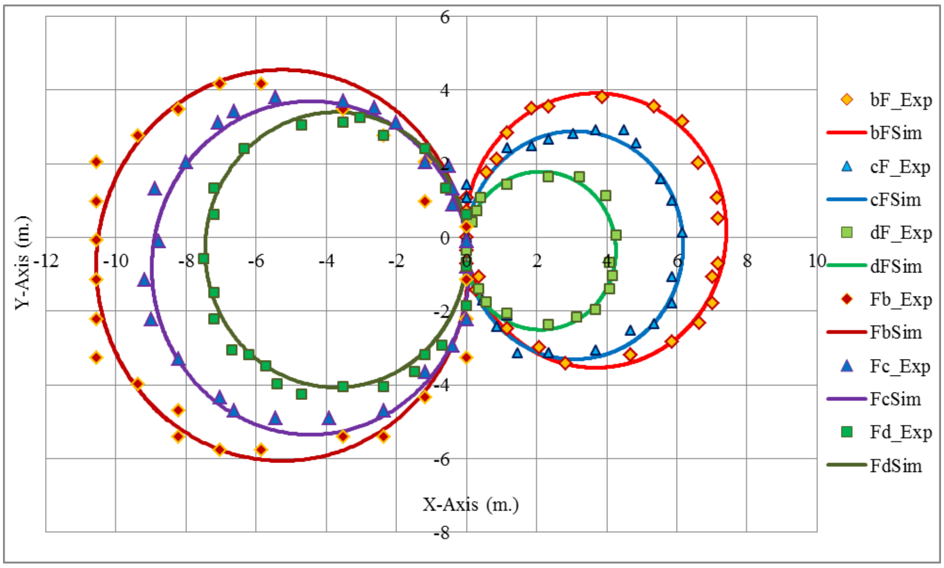

Fig. 9. Comparison of simulation and experimental results of turning tests at different input thrusts

5. CONCLUSION AND FUTURE WORK

In this paper 3 DOF MMG mathematical model of WAM-V is described. The MMG model has been found suitable to model twin hull- twin propeller system like WAM-V. The MMG model has advantages that it models the hull, propeller and their interaction force separately so even if there is any mistake in one part it is not required to change the full model. Manoeuvring derivatives of WAM-V is calculated by the combination of captive model test and system identification method. Turning ability of WAM-V is studied by supplying the different voltages to the portside and starboardside propellers and it is analyzed that turning trajectories are different both the sides due to change in inflow velocity. The MMG model in the simulation shows good agreement with staightline and turning characteristics. In order to better quantify the vehicle dynamics with respect to autonomous control free running open loop model test has enabled significant advances made in the understanding of high speed vehicles like WAM-V. The assessment of system failure conditions in practical situations on WAM-V designs has also been the feature of the free running open loop model test.

The use of free running models also provides the opportunity to test in open water conditions, which not only reduces reliance on high cost test facilities but is also of particular importance for new generation crafts.

It is observed that the WAM-V software and hardware module is sufficient to be used further ship's navigation and control research. 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 designing a suitable robust controller for marine applications.

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