Simulation Of Mariner Class Vessel Using Different Controllers

Ashwin Sekhar A[*,a], Akhilkumar K S[*,b], Ashwin Ramesh[*,c], Parthav Ramesh[*,d], A K D Velayudhan[*,e]

[*] Department of Mechanical Engineering, Muthoot Institute of Technology and Science, Varikoli, 682310, India

[a] 19me084@mgits.ac.in, [b] 19me063@mgits.ac.in, [c] 19me068@mgits.ac.in , [d] 19me256@mgits.ac.in, [e] arunkumardv@mgits.ac.in

Abstract-Marine Industry is a fast developing and a field which is given very much importance these days for the global development in trade and transport. Ships contribute a lot in sea food industry, bulk and heavy materials and fluid transportation and leisure and tourism industries which all are the backbone of any country. But as it is very much important the number of ships that are sailing day by day and the workers working behind this industry is lot. These workers must undergo very severe and high-risk operations in the working which makes there life very much hectic in these ships. To reduce the work effort and the ship trafficking ship navigation autopilot systems where designed. But these Autopilots also has its own flaws or difficulties such as when we set a course the ship may reach at a position which is different from the course which was been set due to environmental disturbances. Therefore, different controllers are used for reducing these errors. In this project mathematical modelling of the ship which is used for installing the controllers for the navigation purpose is discussed and helping to reduce the error which has occurred. It will help us in getting the optimised error as the result it is possible to find which controller can be used as the best for the navigation and the guidance purpose. In mathematical modelling out of 6 degree of freedom 3 degree of freedom (surge, sway, yaw) ship movement is considered. Modelling is based on a large container ship in heading plane. Autopilot circuit is designed in SIMULINK, then the data from mathematical modelling is applied in the closed loop circuit. Final output is analysed using different controllers and mathematical modelling parameters and an optimized value is formed.

Index terms: Marine Hydrodynamics, Marine Control Systems, Floating Body Dynamics

INTRODUCTION

Marine Industry is a fast-growing industry which is the backbone of the bulk product transportations. Ships transport more than 80% of world trade volume and about 70% of trade value. The world fleet that carries seaborne trade involves dry bulk ships, container ships and oil tankers. Also, economic growth of a country lies mainly on its import and exports and as the bulk transportation relies mainly through sea it becomes very important for the development in this sector. The increasing traffic and unpredictable situations in the sea makes it difficult for the workers in the ships to control and navigate the ships. As a result, autopilots were developed. Autopilots control the ship navigation to a course that has been assigned without any manual help. Autopilot is a mechanical, electrical, or hydraulic system which helps in setting the shortest course and it also maintains the course without the need of human assistance. It also guides the vessel around any obstruction when detected and reduces the workload on the crew.

Even though autopilot systems help in navigation process it is not that effective as the position that we get to vary from the course that we have assigned. And this result helps to overcome this error for different kind of controllers. These controllers reduce this error that are occurring and getting to reach the desired position that we must get to. There are varies controllers developed such as PID controllers, PI controllers, PI – PD controllers for controlling parameters such as temperature, pressure, flow, speed, and some other process variables.

PID controllers are the most accurate and stable controllers, and they use a control loop feedback mechanism to control process variables. But PID controllers show poor control performances for a integrating process and a large time delay process and also it cannot incorporate ramp-type set point change or slow disturbances. Several research and developments are carrying out to reduce or eliminate the drawback.

MATHEMATICAL MODELLING OF THE SHIP

Here the kinematics, dynamics and how a vessel behaves according to the different kinds of wind waves and wind generated waves. After which we jumped into the study which includes three degrees of freedom reduced from six degrees of freedom and based on this stage, we could find out the mathematical modelling of a marine vessel based on three degrees of freedom.

During the motion of a marine vessel there are usually six degrees of freedom these are termed as the surge, sway, heave, roll, pitch and yaw as shown in the table 2.1. Based on these degrees of freedom the kinematic behaviour and the dynamic equations of the ship are termed. We will look into these as we move on.

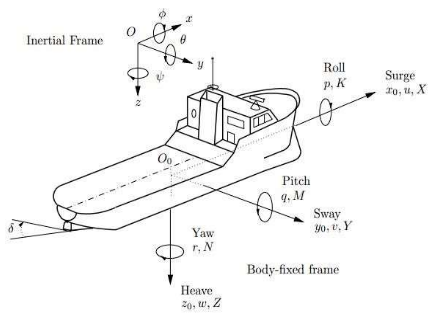

Figure 1. Motion variables for a mariner vessel [4]

The dynamics of a ship can be divided into two parts: kinematics, which considers the geometrical aspects of motion, and dynamics, which is takes the forces causing the motion into account. The main aim here in the discussion is to write the equation of motion of ship in the following way so that controllers can be in cooperated with the model.

The mathematical modelling of the ship is done in such a way that the all the forces acting on the vessel has to be balanced such the expression given below consist of the dynamic terms as well as the environmental disturbances and on further reducing and converting it to the matrix model that has to be inserted into the Simulink model Eq: - Ref[9]

$$\dot{\eta} = J(\eta)v$$
$$Mv + C(v)v + D(v)v \dot{+} g(\eta) = T + g_{\circ} + w$$

Degree of Freedom		Force and Moments	Linear and Angular Velocities	Positions and Euler Angles
1	Motion in x direction(surge)	X	u	x
2	Motion in y direction(sway)	Y	v	y
3	Motion in z direction(heave)	Z	w	z
4	Rotation about x axis (roll, heel)	K	p	ø
5	Rotation about y axis (pitch, trim)	M	q	θ
6	Rotation about z direction(yaw)	N	r	Ψ

Table 1. Directions and notation

When looking into kinematics it involves the geometry, velocity, acceleration, displacement etc. But in the case of locating of ships we have different frames of references and it is required to transfer a geometric quantity from one frame of reference to the b frame so therefore we use the rotation matrix R. When this matrix is multiplied by a quantity it is transferred from one frame of reference to the other. Ref[9]

$$v^{\omega} = R^{\omega}_{from}\, v^{from}$$

Where the R matrix is of the form Ref[9]

: -

$$R^n_b(\theta) = \begin{matrix} c\varphi c\theta & -s\varphi c\emptyset + c\varphi s\theta s\varphi & s\varphi s\emptyset + c\varphi c\emptyset s\theta \\ s\varphi c\theta & c\varphi c\emptyset + s\emptyset s\varphi & -c\varphi s\emptyset + s\theta s\varphi c\emptyset \\ -s\theta & c\theta s\emptyset & c\theta c\emptyset \end{matrix}$$

After transferring this to the required frame of reference we find the acceleration in each axis's and finally design the forces and the external factors for adding into the mat lab. According to which the velocity after rotation to another frame it can be written as follows Ref[9]

.

$$\begin{aligned} v^n_c &= R^n_b(v^b_o + \dot{\omega}^b_{nb} \times r^b_g + \omega^b_{nb} \times \dot{r}^b_g) + \dot{R}^n_b(v^b_o + \omega^b_{nb} \times r^b_g) \\ &= R^n_b\left(\dot{v}^b_o + \dot{\omega}^b_{nb} \times r^b_g\right) + R^n_b S\left(\omega^b_{nb}\right)\left(v^b_o + \omega^b_{nb} \times r^b_g\right) \\ &= R^n_b[\dot{v}^b_o + S\left(\dot{\omega}^b_{nb}\right)r^b_g + S\left(\omega^b_{nb}\right)v^b_o + S^2(\omega^b_{nb})r^b_g \end{aligned}$$

After differentiating this velocity component and then by multiplying this component with the mass component and finally removing the minute differences we can write the equation of translational motion as follows Ref[9]

$$m(\dot{v}^b_c + S\left(\omega^b_{nb}\right)v^b_c = f^b_c$$

As the expanded form is hard for computing we represent the vectorial representation of the 6 DOF rigid body equation of motion Ref[9]

$$M_{RB}\dot{v} + C_{RB}(v)v = \tau_{RB}$$

$$M_{RB} = \begin{bmatrix} m & 0 & 0 & 0 & mz_G & -my_G \\ 0 & m & 0 & -mz_G & 0 & mx_G \\ 0 & 0 & m & my_G & -mx_G & 0 \\ 0 & -mz_G & my_G & I_x & -I_{xy} & -I_{xz} \\ mz_G & 0 & -mx_G & -I_{yx} & I_y & -I_{yz} \\ -my_G & mx_G & 0 & -I_{xx} & -I_{xy} & I_x \end{bmatrix}$$

$$C_{RB}(v) = \begin{bmatrix} 0 & 0 & 0 & m(y_{Gq} + z_{Gr}) & -m(y_{Gq} - w) & -m(x_{Gr} + v) \\ 0 & 0 & 0 & -m(y_{Gp} + w) & m(z_{Gr} + x_{Gp}) & -m(y_{Gr} + u) \\ 0 & 0 & 0 & m(z_{Gp} - v) & -m(z_{Gp} + u) & m(x_{Gp} + y_{Gq}) \\ -m(y_{Gq} + z_{Gr}) & m(y_{Gp} + w) & m(z_{Gp} - v) & 0 & -I_{yzq} - I_{xzp} + I_{zr} & I_{yzr} + I_{xyp} + I_y q \\ m(y_{Gq} - w) & -m(z_{Gr} + x_{Gp}) & m(z_{Gp} + u) & I_{yzq} + I_{x\,zp} - I_{zr} & 0 & -I_{xz}r - I_{zy}q - I_z p \\ m(x_{Gr} + v) & m(y_{Gr} - u) & -m(x_{Gp} + y_{Gq}) & I_{yzr} - I_{xyp} + I_{yq} & I_{xzr} + I_{zyq} - I_{zp} & 0 \end{bmatrix}$$

As we have found out the equations of motion in the six degrees of freedom now, we reduce this model to a model consisting of three degrees of freedom. As the huge marine vessels have reduced pitch movements, we can reduce these factors and reduce this to three degrees of freedom consisting of surge, sway and yaw. As there is only three degrees of freedom following approximations can be made:

$$\varphi^{\cdot} = p \quad \psi^{\cdot} = r.\cos(\varphi)$$

But these equations only consist of the forces due to the movement of the ship but we haven't considered the environmental disturbances into consideration. These includes forces due to wind, force due to wind generated waves. So to analyse this situation and disturbances we analyse this under two conditions one is under the sea keeping condition and the other is under the manoeuvring condition. Where in the sea keeping condition the ship movement is considered under the still sea and in manoeuvring condition the ship is still while the waves and winds and other environmental disturbances take place. In order to account all these environmental disturbances and the geometric aspects of the ship we take hydrodynamic coefficients which is given by the formulae Ref [9]: -

$$\begin{aligned} X_A = {} & X_{\dot{u}}u + X_{\dot{w}}(\dot{w} + uq) + X_{\dot{q}}\dot{q} + Z_{\dot{w}}wq + Z_{\dot{q}}q^2 + X_{\dot{v}}\dot{v} \\ & + X_{\dot{p}}\dot{p} + X_{\dot{r}}\dot{r} - Y_{\dot{u}}ur - Y_{\dot{p}}rp - Y_{\dot{r}}r^2 \\ & - X_{\dot{u}}ur - Y_{\dot{w}}wr + Y_w vq + Z_{\dot{p}}pq \\ & - \left(Y_{\dot{q}} - Z_{\dot{r}}\right)qr \end{aligned}$$

$$\begin{aligned} Y_A = {} & X_{\dot{u}}u^{\cdot} + Y_w\dot{w} + Y_{\dot{q}}\dot{q} + Y_{\dot{u}}\dot{u} + Y_{\dot{p}}\dot{p} + Y_{\dot{r}}\dot{r} + X_{\dot{u}}ur \\ & - Y_{\dot{w}}vp + X_{\dot{r}}r^2 + \left(X_{\dot{p}} - Z_{\dot{r}}\right)rp \\ & - Z_{\dot{p}}p^2 - X_{\dot{w}}(up - wr) \\ & + X_{\dot{u}}ur - Z_{\dot{w}}wp - Z_p pq + X_{\dot{q}}qr \end{aligned}$$

$$\begin{aligned} Z_A = {} & X_{\dot{w}}(u - wq) + Z_{\dot{w}}\dot{w} + Z_{\dot{q}}\dot{q} - X_{\dot{u}}uq - X_{\dot{q}}q^2 \\ & + Y_{\dot{w}}\dot{v} + Z_{\dot{p}}\dot{p} + Z_{\dot{r}}\dot{r} + Y_{\dot{v}}vp + Y_{\dot{r}}rp \\ & + Y_{\dot{p}}p^2 + X_{\dot{u}}up + Y_{\dot{w}}wp - X_{\dot{v}}vq \\ & - \left(X_{\dot{p}} - Y_{\dot{q}}\right)pq - X_{\dot{r}}qr \end{aligned}$$

$$\begin{aligned} K_A = {} & X_{\dot{p}}\dot{u} + Z_{\dot{p}}\dot{w} + K_{\dot{q}}\dot{q} - X_{\dot{u}}wu + X_{\dot{r}}uq - Y_{\dot{w}}w^2 \\ & - \left(Y_{\dot{q}} - Z_{\dot{r}}\right)wq + M_{\dot{r}}q^2 + Y_{\dot{p}}v \\ & + K_{\dot{p}}\dot{p} + K_{\dot{r}}\dot{r} + Y_{\dot{w}}v^2 - \left(Y_{\dot{q}} - Z_{\dot{r}}\right)vr \\ & + Z_{\dot{p}}vp - M_{\dot{r}}r^2 - K_{\dot{r}}rp + K_{\dot{w}}uv \\ & - (Y_{\dot{u}} - Z_{\dot{w}})vw - \left(Y_{\dot{r}} + Z_{\dot{q}}\right)wr \\ & - Y_{\dot{p}}wp - X_{\dot{q}}ur + \left(Y_{\dot{r}} + Z_{\dot{q}}\right)vq \\ & + K_{\dot{r}}pq - \left(M_{\dot{q}} - N_{\dot{r}}\right)qr \end{aligned}$$

$$\begin{aligned} M_A = {} & X_{\dot{q}}(\dot{u} + wq) + Z_{\dot{q}}(\dot{w} - uq) + M_{\dot{q}}\dot{q} \\ & - X_{\dot{w}}(u^2 - w^2) - (Z_{\dot{w}} - X_{\dot{u}})wu \\ & + Y_{\dot{q}}\dot{v} + K_{\dot{q}}\dot{p} + M_{\dot{r}}\dot{r} + Y_{\dot{p}}vr - Y_{\dot{r}}vp \\ & - K_{\dot{r}}(p^2 - r^2) + (K_{\dot{p}} - N_{\dot{r}})rp \\ & - Y_{\dot{w}}uv - X_{\dot{v}}vw - (X_{\dot{r}} + Z_{\dot{p}})(up \\ & - wr) + (X_{\dot{p}} - Z_{\dot{r}})(wp + ur) \\ & - M_{\dot{r}}pq + K_{\dot{q}}qr \end{aligned}$$

$$\begin{aligned} N_A = {} & X_{\dot{r}}\dot{u} + Z_{\dot{r}}w^{\cdot} + M_{\dot{r}}\dot{q} + X_{\dot{v}}u^2 + Y_{\dot{w}}wu - (X_{\dot{p}} \\ & - Y_{\dot{q}})uq - Z_{\dot{p}}wq - K_{\dot{q}}q^2 + Y_{\dot{r}}\dot{v} \\ & + K_{\dot{r}}\dot{p} + N_{\dot{r}}\dot{r} - X_{\dot{v}}v^2 - X_{\dot{r}}vr - (X_{\dot{p}} \\ & - Y_{\dot{q}})vp + M_{\dot{r}}rp + K_{\dot{q}}p^2 - (X_{\dot{u}} \\ & - Y_{\dot{v}})uv - X_{\dot{w}}vw + (X_{\dot{q}} + Y_{\dot{p}})up \\ & + Y_{\dot{r}}ur + Z_{\dot{q}}wp - (X_{\dot{q}} + Y_{\dot{p}})vq \\ & - (K_{\dot{p}} - M_{\dot{q}})pq - K_{\dot{r}}qr \end{aligned}$$

From the vectorial representation we can reduce this six-degree matrix to three-degree matrix. as the ship is moving in the manuering condition we can neglect the forces acting in the directions other than surge, sway and yaw and this matrix is represented as: -

$$\begin{bmatrix} m - Y\dot{v}_r & -N_{\dot{v}_r} & 0 & 0 \\ -N_{\dot{v}_r} & I_{zz} - N_{\dot{r}} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{v}_r \\ \dot{r} \\ \dot{r} \\ \dot{Y} \end{bmatrix} =$$

$$\begin{bmatrix} Y_{v_r} & Y_{r\_}mU_0 & 0 & 0 \\ N_{v_r} & Y_{v_r}N_r & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 1 & 0 & U_0 & 0 \end{bmatrix} \begin{bmatrix} v_r \\ r \\ \varphi \\ Y \end{bmatrix} + \begin{bmatrix} Y_\delta \\ N_\delta \\ 0 \\ 0 \end{bmatrix} \delta_r(t)$$

Now this mathematical model is inserted into the Simulink where each PID and PD controllers are designed for the steering of the ship under the manuering condition.

MATLAB SIMULINK CIRCUIT AND RESULTS

After the mathematical modelling of the ship consisting of all the hydrodynamic coefficients and the other required parameters such as surge velocity, yaw velocity etc are expressed in a state space form, then designed a Simulink circuit that have modelled for incorporating PD and PID controller circuits. These controllers will provide the final output results or over response results of each controller.

The **PD circuit** stands for the proportional derivative controller. This controller has a proportional and a derivative part for its controller motion. Here the basic principle is the initial stage is passed through the proportional mode and after passing through the mathematical model the derivative of the position has been taken and it is compared with the required result. If there is an error from the required result the controller continues this process till the right exact output has been obtained.

Now getting to the Simulink model, we initially have a step where we give the range of the input to the output values. These values pass into the summation where the input value and the output value is compared and passed on as the error now this error is added to the input value and passed on to the mathematical mode; and after passing through it we obtain the results for each parameters after processing through the model. These results are separated to four different outputs as shown in fig and these results runs back to the initial summation and it is compared again to obtain the error and the result is obtained.

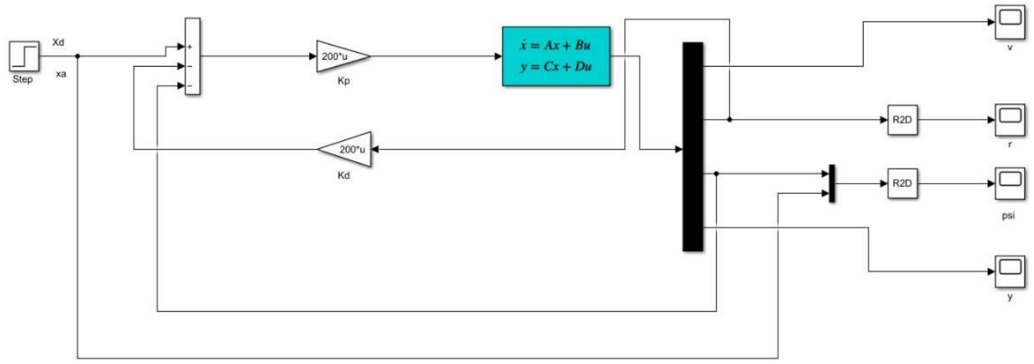

Figure 2. Simulink circuit for PD controller for manuering condition

In PID model consists of a proportional derivative and integration parts. Here the main advantage of this controller is that it can remove the steady state error that occurs in the PD controller. It also has an added advantage such that it can eliminate the overshooting of the required results. This is eliminated by the derivative and the proportional parts. Here the Simulink modelling is same as that of PD controllers with inbuilt option of PID controllers in the MATLAB Simulink. The input value initially passes through this controller the proportional and integration function updates this value and treats it to the model the model process these and produces the final outputs and then the final output value is compared with the initial value, and they are summed together to add the error to the results and removing it.

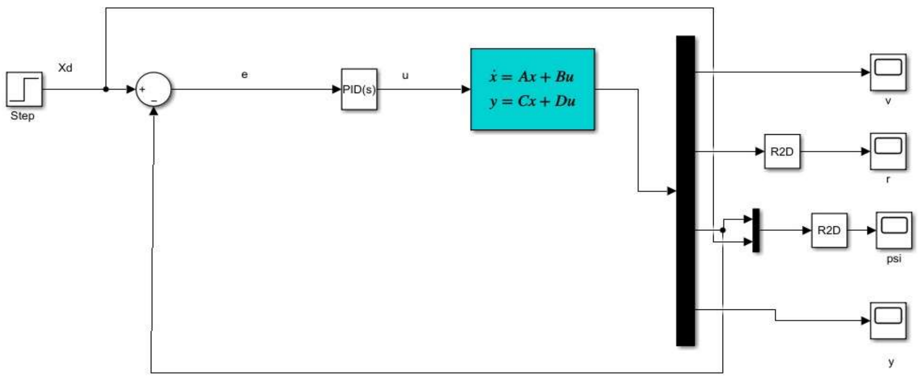

Figure 3. Simulink circuit for PID controller for manuering condition

RESULTS OBTAINED

After running the Simulink model, the results for the angular velocity, linear velocity, the movement of the ship and the rotation of ship in response to the autopilot steering system and the result obtained are shown below for both the controllers.

PD Results

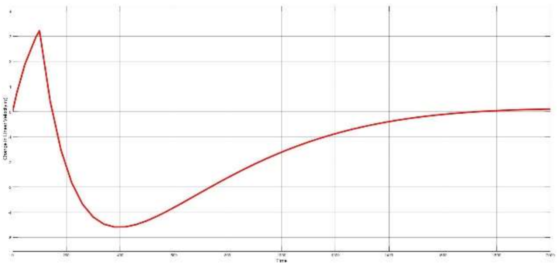

Figure 4 Graph obtained for change in linear velocity with respect to time.

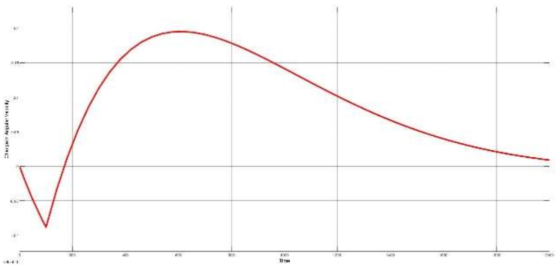

Figure 5 Graph obtained for change in Angular velocity with respect to time.

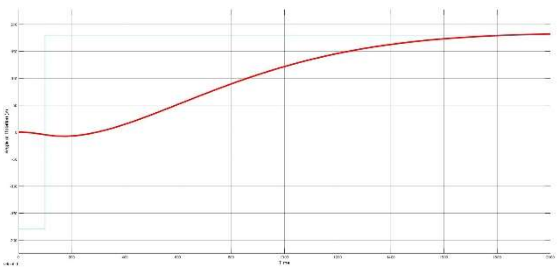

Figure 6 Graph obtained for Angular Rotation with respect to time.

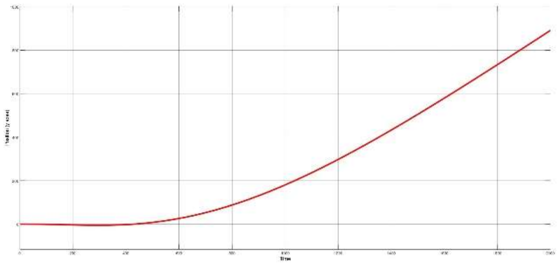

Figure 7 Graph obtained for position with respect to time.

PID Results

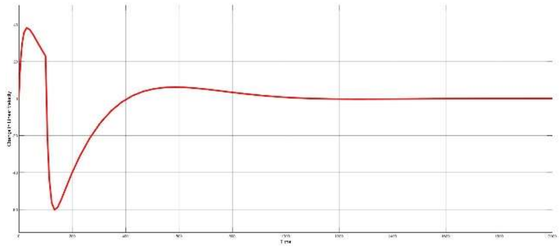

Figure 8 Graph obtained for change in linear velocity with respect to time.

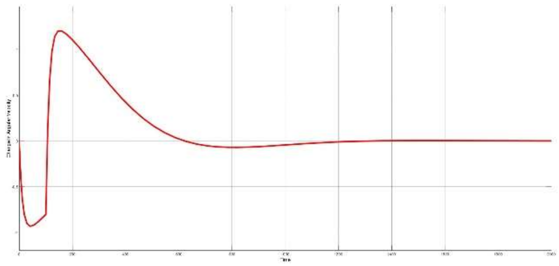

Figure 9 Graph obtained for change in Angular velocity with respect to time.

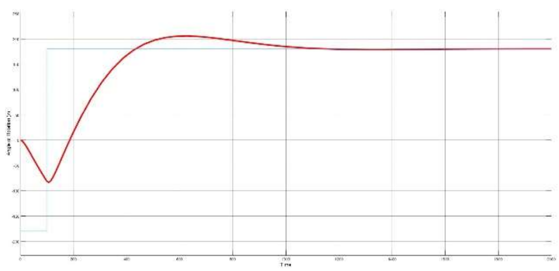

Figure 10 Graph obtained for Angular Rotation with respect to time.

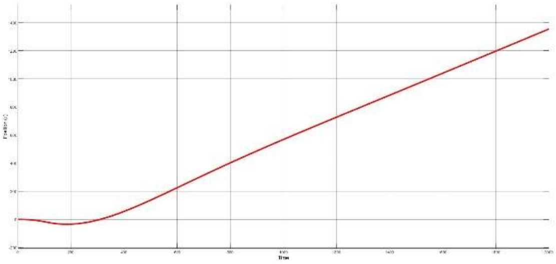

Figure 11 Graph obtained for Position with respect to time.

After analysing both the results we can see PID controllers attain more stability that the PD controllers in less time thus stating that PID controllers are much more efficient that PD controllers for this model of the ship.

CONCLUSION

Based on the studies different kinds of controllers where identified. For performing the project, the mathematical modelling of the vessel consisting of both the parameters due to the movement of the ship and environmental disturbances where also taken into consideration. When analysing the mathematical model, I consist of the forces due to the control systems, hydrostatic term, and environmental disturbances. By using the Newtonian approach and the principle of superposition the mathematical modelling is performed. Now this mathematical model can be introduced into the control systems which can be used for obtaining the result. Based on these results we can obtained the optimized controller. Using the literature reviews, we could reduce the six degrees of freedom to the four degrees of freedom.

REFERENCES

[1] Aumtab, Chatchawan, and ThanapatWanichanon. 2022. "Stability and Tracking Control of Nonlinear Rigid-Body Ship Motions" Journal of Marine Science and Engineering 10, no. 2: 153 https://doi.org/10.3390/jmse10020153

[2] Bouteraa, Yassine, Khalid A. Alattas, Saleh Mobayen, Mehdi Golestani, Atef Ibrahim, and Usman Tariq. "Disturbance Observer-Based Tracking Controller for Uncertain Marine Surface Vessel." In Actuators, vol. 11, no. 5, p. 128. MDPI, 2022.

[3] Zhang, Hugan, Xianku Zhang, and Renxiang Bu. “Sliding mode adaptive control for ship path following with sideslip angle observer.” Ocean Engineering 251 (2022): 111106

[4] Huang,Haifeng, mohammadaminShirkhani, JafarTavoosi, and Omar Mahmoud. “A New Intelligent Dynamic Control Method for a Class of Stochastic Nonlinear Systems.” Mathematics 10, no. 9 (2022): 1406.

[5] Qu, Zhenyu. "Research on Automatic Berthing Method of Intelligent Ship”. “International Core Journal of Engineering 7.3 (2021): 419-424”.

[6] Wang, Liuping. PID control system design and automatic tuning using MATLAB/Simulink. John Wiley & Sons, 2020.

[7] Z. Li and J. Sun, "Disturbance Compensating Model Predictive Control with Application to Ship Heading Control," in IEEE Transactions on Control Systems Technology, vol. 20, no. 1, pp. 257-265, Jan.2012, doi:10.1109/TCST.2011.2106212.

[8] Cheng, Jin, Jiangqiang Yi, and Dongbin Zhao. "Design of a sliding mode controller for trajectory tracking problem of marine vessels." IET control theory & applications 1, no. 1 (2007): 233-237.

[9] Fossen, Thor I. "Marine Control Systems" University of Trondheim, Norway, Printed and bound by Tapir Trykkeri, Trondheim, Norway, ISBN: 82-92356-00-2 (2002).

[10] Fossen, Thor I. "Guidance and Control of Ocean Vehicles." University of Trondheim, Norway, Printed by John Wiley & Sons, Chichester, England, ISBN: 0 471 94113 1, Doctors Thesis (1999).