Controlled Roll Motion of Ships Using PID Controller with Actuator Delay

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Abstract- In the event of non-linear motion of ships, the amplitudes of roll motion can have sudden jumps in a certain range of frequency. Such large amplitudes are often disastrous to the ship and can have undesired effects. These large amplitudes need to be attenuated in order to prevent undesirable consequences. Several methods are used for avoiding such large amplitudes. One such solution to decrease the large roll amplitude is to introduce fin stabilizers on either side of the ship. These fin stabilizers can function in such a way as to produce a lift which can reduce the roll moment which could have lead to the large roll amplitudes. In the paper, an attempt is done to reduce this roll motion using conventional PID controller method. The controller is applied when the roll amplitude exceeds a reference value. The PID algorithm identifies a suitable alignment for the fin such as to produce a lift required to reduce the roll amplitude. The effect of the controller on the roll motion is analyzed and compared to the normal rolling motion without the controller. Also, the controller is applied at varying time lag to study the effect of the delay in applying the controller on the resulting amplitude using an actuator delay. The different delays are compared and analyzed using numerical simulation in MATLAB**.**

Index Terms- Actuator Delay, PID Controller, Vortex Panel, Duffing Equation, Fin stabilizer

I. INTRODUCTION

Rolling is one of the most important phenomenon in ship motions. Large rolling amplitudes has led to the capsizing of a number of vessels over the past year. Stability against capsizing is one of the fundamental requirements in ship design. Large roll amplitudes can cause critical loads on sea fastenings, shifting of cargo, shipping of water, loss of men and deck equipment overboard, and possibly loss of control over the ship. The undesirable effects of roll motion became more noticeable in the mid-9th century when significant changes were introduced to the design and development of ships. Developments like the replacement of sails with steam engine, wood by iron and the transition of warship arrangement from batteries to turrets led to modifications of the transverse stability with the consequence of large roll motion.

For small angles of roll motions, the response of ships can be described by a linear equation. However, as the amplitude of oscillation increases nonlinear effects come into play. Nonlinearity can magnify small variations in excitation to the point where the restoring force contributes to capsizing. The nonlinearity is due to the nature of restoring moment and damping. The environmental loadings are nonlinear and beyond the control of the designer.

As a result, many studies have been conducted to reduce the amplitude of rolling of ships using anti-rolling tanks, bilge keels and stabilizer fins. Active stabilizing fins are good instruments to reduce such large amplitudes in ship rolling. A pair of fins is attached to the lateral sides of the ship. The fins act as a control device which reduces the rolling motion. Most control devices rely on feedback control. The stabilizer fins are also based on a feedback control system. Here a PID controller is used with an actuator delay to analyse its effectiveness in minimizing the roll amplitude.

II. MODELLING

Duffing model

The rolling motion of the ship is modelled using a non-linear equation. Here the model equation under consideration is the Duffing equation. Previously authors have tried to understand the roll motion using the generalized Duffing equation to yield reasonably good results. The Duffing roll equation was also analytically solved using harmonic balance method. The roll equation is given as:

$$(I+\delta I)\ddot{\phi}+B(\dot{\phi},\phi)+\Delta GZ\phi=\omega_e^2\alpha_m I_{xx}\cos\omega_e t$$

The ship is subjected to a sinusoidal force with no phase lag. Nonlinearity is accounted in the damping and restoring moment. The damping for barges and ships with large slenderness ratio is often nonlinear. The value of GZ was calculated from the GZ curve. The nonlinearity in the restoring moment was assumed to be cubic. The roll motion equation for the resulting nonlinear system is given below:

$$\ddot{\phi}+b_L\dot{\phi}+b_N\dot{\phi}|\dot{\phi}|+\omega_\varphi^2\phi+m_3\phi^3=\lambda\omega_e^2\alpha_m\cos(\omega_e t)$$

Where

$$\omega_e^2=\frac{\Delta GM}{I_{xx}+\delta I_{XX}}$$

$$m_3=\frac{4\omega_\Phi^2}{\phi_V^2}\left[\frac{3A_{\phi v}}{GM\phi_V^2}-1\right]=1500.22$$

$$b_L=\frac{B_L}{I_{xx}+\delta I_{XX}}=0.903$$

$$b_N=\frac{B_N}{I_{xx}+\delta I_{XX}}=0.0903$$

damping parameters were determined from empirical correlations. The restoring force coefficient is obtained from the value of metacentric height. The metacentric height was obtained from the inclining experiment carried out in the towing tank of marine hydrodynamics laboratory at IIT Kharagpur.

Vortex Panel Method

The purpose of fins are to provide lift moment to counteract the rolling moment. The lift coefficient of the hydrofoil was calculated using vortex panel method. Analytical solution to the flows along airfoils are valid only if they can be considered as thin airfoils. This is where the importance of panel method arises. They are numerical methods based on the division of the airfoil section into panels. The vortex pane method, in particular, is used for the calculation of lifting flows. It involves modelling the flow past an airfoil as the summation of a uniform flow and a series of vortex panels. The panel are chosen is such a way that the polygon formed using them approximately forms the curved shape of the airfoil.

Suppose the airfoil section is divided into m panels. In the presence of a uniform flow the velocity potential at the ith control point (xi, yi) is given as

$$\phi(x_i,y_i)=V_\infty(x_i\cos\alpha+y_i\sin\alpha)-\sum_{j=1}^{m}\int_j\frac{\gamma(s_j)}{2\pi}\tan^{-1}\left(\frac{y_i-y_j}{x_i-x_j}\right)ds_j$$

Where

$$\gamma(s_j) = \gamma_j + (\gamma_{j+1} - \gamma_j)\frac{s_i}{s_j}$$

$$\sum_{=1}^{m}\left(Cn1_{ij}\,\gamma'_j + Cn2_{ij}\,\gamma'_{j+1}\right) = \sin(\theta_i - \alpha)$$

The basic equation for the panel method, after carrying out differentiation and integration on the above equation, is obtained as

$$\sum_{=1}^{m}\left(Cn1_{ij}\,\gamma'_j + Cn2_{ij}\,\gamma'_{j+1}\right) = \sin(\theta_i - \alpha) \qquad i = 1,2'.....m$$

Where θ is the orientation angle and $\gamma' = \gamma / 2\pi V_\infty$ is the dimensionless circulation density.

The kutta condition which ensures smooth flow along the trailing edges is applied as

$$\gamma'_1 + \gamma'_{m+1} = 0 \quad i = 1,2....,m+1$$

The dimensionless velocity will be calculated as:

$$V_i = \cos(\theta_i - \alpha) + \sum_{j=1}^{m}(Cn1_{ij}\,\gamma'_j + Cn2_{ij}\,\gamma'_{j+1} \qquad i = 1,2,....m$$

At the ith control point the pressure coefficient is obtained as

$$C_{pi} = 1 - V_i^2$$

Integrating the pressure coefficient over the airfoil, the lift coefficient can be obtained as

$$C_L = \int_{TE}^{LE} C_p\, d(x/c)$$

Subsequently the lift is thus calculated from,

$$L = 0.5 C_L \rho A V^2$$

NACA 0020 airfoil is used for the study and the lift coefficient obtained for various angle of attacks using vortex panel method are provided in Fig. 1.

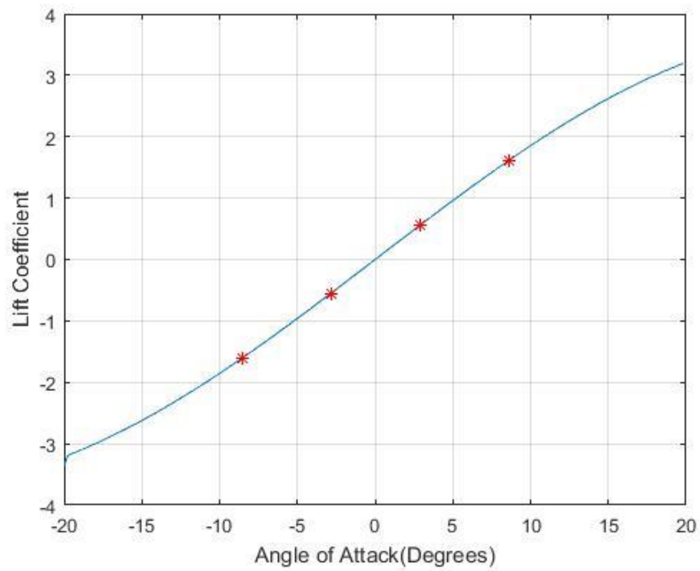

Figure 1. Lift v/s angle of attack

The values of lift coefficient obtained from the vortex panel method are checked using X-foil (a program used for the design and analysis of airfoil) to verify the result.

Control motion using active fin stabilizers

Fins stabilizers consist of a pair of hydrofoils mounted on rotatable stocks at the turn of the bilge located about amidships. As the ship rolls, this motion is sensed via gyroscopes and fed back to the control system, which commands the actuator to modify the angle of incidence of the fins. Once there is an angle between the flow and the fin, hydrodynamic lift is generated, and a stabilizing moment is obtained as a result of the generated lift and the location of the fins on the hull. As in any lifting device, the amount of lift, and hence the generated moment, depend on the vessel speed.

The fins continue to generate the lift until the rolling amplitude is less than the prescribed value. This ensures that rapid jump in the amplitude of the roll is prevented. The lift was given as a negative control moment in the Duffing equation to reduce the effect of the forcing moment. The rolling equation can be written as:

$$(I + \delta I)\ddot{\phi} + B\left(\dot{\phi}, \phi\right) + \Delta GZ\phi = \omega_e^2 \alpha_m I_{xx} \cos \omega_e t - M_L$$

Where $M_{L=}\ 0.5C_L AV^2 L$, L being the lever arm, V is the ship speed, A is the fin area and C_L is the lift coefficient. Here the lift obtained from the vortex panel method is applied to the rolling equation when the amplitude is higher than a particular value based on PID control feedback system

PID Control System

In the study, conventional PID controller system is used for stabilizing the roll motion. The purpose of controller is to reduce the roll amplitude of the ship with minimum control action. The PID controller acts as a feedback mechanism in stabilizing the roll amplitude. It is provided with a reference value for the allowable roll amplitude. The controller aligns the fins in such a way as to provide sufficient lift to bring down the roll amplitude to the desired level. The parameters of PID controller lead to different effects on system characteristics. The proportional block provides an overall control action, and the integral block reduces steady-state errors and the derivative block improves transient response. The classical PID control system is shown as:

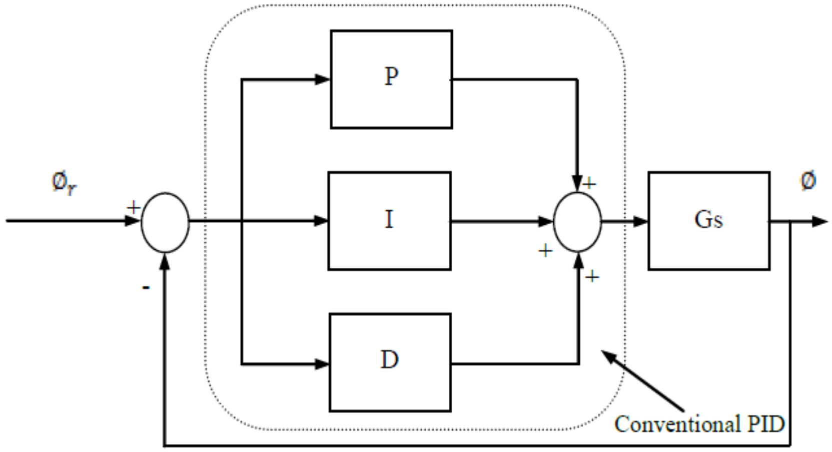

Figure 2. PID Control system flow chart

Generally, the transfer function of a PID controller is given as:

$$G_{pid}(t) = K_P \left[e + \frac{1}{\tau_I} \int de(t)dt + \tau_d \frac{de(t)}{dt} \right]$$

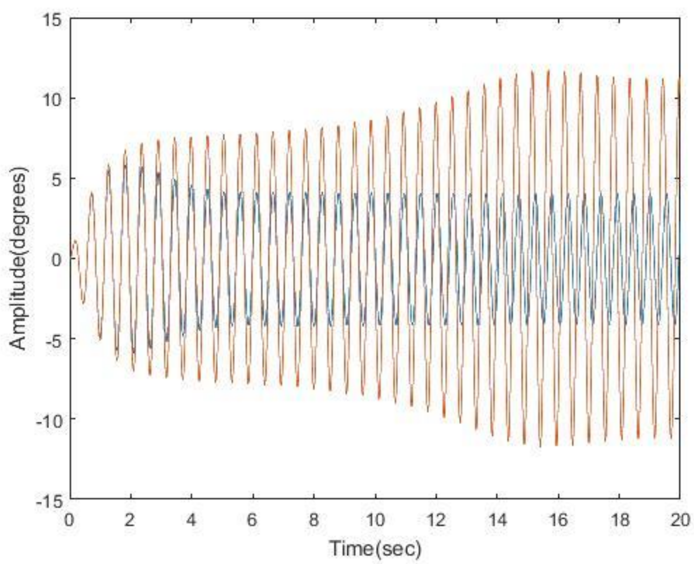

Figure 3. Controlled(blue) v/s Uncontrolled(red) time series response

Actuator delay in control action

The time at which the application of feedback from the fins is provided is crucial to the response. Therefore, the PID output is applied to the fins after a specific time lag to study its influence on the roll amplitude response. The response was analysed for different time lags and the results are as shown.

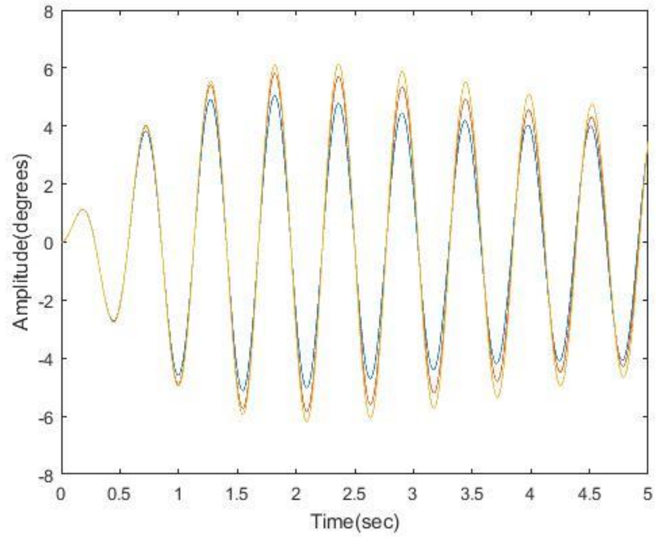

Figure 4. Time series response for actuator delay of (a) 1 sec (b) 3 secs (c) 5 secs

The actuator delay was studied for a time lag of 1 sec, 3 sec and 5 sec. The increase in delay in the actuator application can be seen to result in relatively higher amplitudes.

I. CONCLUSION

This study presents the control of non-linear roll motion of ships with PID controller with actuator delay. The non- linear terms which takes restoring and damping coefficients are calculated using empirical equations. In the study, the application of fin roll stabilizers using PID controller has shown to reduce the roll amplitude considerably. The system response to the application can also vary depending on the time lag of the actuator delay. The results have shown conclusively that PID controllers in fin stabilizers are thus an efficient way to minimize large amplitudes in rolling motion.

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