

On Design of Digital Lead-Lag Compensators for Ship Roll Stabilization

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Abstract – The paper discusses ship roll stabilization utilizing integrated fin rudder roll stabilizers based on the linearized ship model. Digital lead-lag compensators are used for fin roll and rudder roll stabilization as well as for ship yaw motion control and they are designed by using Bode plots method. According to the results of the digital simulation, digital lead-lag compensators may be able to reduce roll motion more effectively than conventionally designed digital PID controllers.

Key words: stabilization, ship vessel navigation, digital PID control, digital lead-lag compensator, rudder control, fin control

I. INTRODUCTION

The most crucial component of ship stability is roll stabilization, which has been extensively studied in recent decades [1-4]. Excessive roll motion can result in ship flipping, cargo damage and loss, and motion sickness among the crew. The precision of ship-borne weapons, the regular operation of radars and other equipment, and the capacity of navy boats to launch and land helicopters or airplanes will all be impacted. As a result, it is crucial to reduce the ship's roll motion when turning and navigating in a straight path.

Moving weights, active tanks, gyroscope stabilizers, fin roll (FR) and rudder roll (RR) stabilizers, or the combination of the last two, known as integrated fin rudder roll (INFRR) stabilizer, are some of the active devices that help reduce roll [2, 3, 5-9]. The fin stabilizers in beam sea may give more than 90% roll dampening. It is lower during quartering and following sea, but it can be raised by employing a cascade control mechanism, which is responsible for modifying the fin's deflection in order to attain the appropriate effective angle of attack of the water flow on the fin. Fin stabilizers and gyro stabilizers have proven to be the most effective solutions. However, there has been growing interest in using the rudder as an extra roll-reduction device [7, 10] to assist stabilizing fins since rudder roll stabilization devices can provide significant roll reduction. An analysis of the yaw and roll interactions indicated that using the rudder for roll stabilization has only a minimal impact on the ship's yaw response [11].

Various control algorithms have been proposed to stabilize a ship's roll motion, including PID control [5, 12-18], H_2/H_∞ control [1, 11], model reference adaptive control [19], sliding mode control [12, 13], linear quadratic control [20], model predictive control [9]. This paper is an extension of the work presented in [21], which considers INFRR stabilization, in the way that it discusses the digital implementation of lead-lag compensators designed by using Bode plots approach [22]. Digital PID controllers are tuned

by the same method as well, and simulation results of implementation of both sets of control algorithms are compared with the results obtained with digital PID controllers adjusted by the trial-and-error method [12, 13]. According to the simulation results, the digital lead-lag compensators provide a slightly better roll reduction than the digital PID controllers.

II. MODEL OF SHIP ROLL STABILIZATION SYSTEM

The ship roll stabilization system is nonlinear and, therefore, a linear approximation is usually implemented to simplify the modelling process [11]. That results in linear MIMO ship model consisting of three subsystems, which represent fin-roll, rudder-roll and rudder-yaw dynamics. The stabilizing fins' placement and hull design give a very small fin to yaw cross pair term and that is why it is not considered in the model. The transfer functions describing fin-roll, rudder-roll and rudder-yaw dynamics are taken from [12, 13] in the following forms:

$$W_{FRD}(s) = \frac{0.1061(s+1)}{4s^2 + 1.0552s + 2.6808}, \quad (1)$$

$$W_{RRD}(s) = \frac{-0.0704s + 0.0176}{(s + 0.1667)(s^2 + 0.2638s + 0.6703)}, \quad (2)$$

$$W_{RYD}(s) = \frac{-0.0159}{s(s + 0.16)}, \quad (3)$$

respectively. The rudder-roll nonminimum phase dynamics is considerably faster than rudder-yaw dynamics so the cross-coupling can be neglected, enabling the design of rudder-yaw control loop independently from the design of rudder-roll stabilization control.

During the design procedure of compensators (controllers), the first-order transfer functions [12, 13]:

$$W_{FS}(s) = \frac{2}{s+2}, \quad (4)$$

$$W_{RS}(s) = \frac{1.8}{s+1.8}, \quad (5)$$

is used to approximate the dynamics of fin and rudder servo, respectively, although these actuators possess highly nonlinear behavior due to their performance limitations introducing maximum excursion angles and slew-rate nonlinearities into the steering and stabilization systems. These limitations are: the rudder's maximum angle $\pm 40^\circ$ (0.698 rad), and its slew rate $\pm 3.5^\circ/\text{s}$ (0.061 rad/s), the fin's maximum angle of $\pm 25^\circ$ (0.436 rad), and its slew rate $\pm 23.5^\circ/\text{s}$

(0.41 rad/s) [12, 13]. This is shown in Fig. 1, and integrated into the ship roll stabilization model instead of the linear models (4) and (5) during digital simulation.

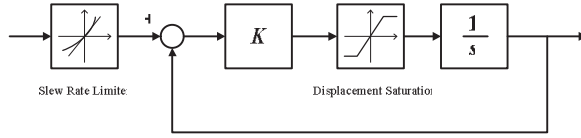


Fig. 1. Fin & rudder servo system model with slew rate limitation and displacement saturation ($K = 2$ for the fin and $K = 1.8$ for rudder servo)

The hydrodynamic interaction between the sea and the hull of the ship is considered as external disturbances. The wave height and encounter frequency determine how severe the impacts on roll and yaw are. The frequency at which waves strike the ship's hull is taken as the encounter frequency. The beam sea waves are simulated by a white noise generated signal that is fed into a band-pass filter [12, 13]:

$$W_{BPF}(s) = \frac{0.1}{s^2 + 0.06s + 0.16}, \quad (6)$$

Finally, roll and yaw perturbations are obtained by using modified the ship's roll and yaw dynamics in the form of waves to roll and waves to yaw transfer functions:

$$W_{WR}(s) = \frac{0.0208s + 0.0751}{s^2 + 0.2535s + 0.5859}, \quad (7)$$

$$W_{WY}(s) = \frac{-0.0159}{s(s + 0.16)}, \quad (8)$$

respectively.

III. DESIGN OF DIGITAL LEAD-LAG COMPENSATORS

Three differently designed sets of control algorithms, each for one triplet of subsystems, are presented in this section. The first set assumes three digital lead-lag compensators for ship heading and roll stabilization, whereas the second one is based on two digital PID controllers for fin-roll and rudder-yaw dynamics and one digital lead-lag compensator for rudder-roll control loop, all designed by using Bode plots method. Finally, the third set of three digital PID controllers provided by the trial-and-error method is given for the comparison purposes.

Lead-lag compensators are first designed in the continuous-time domain by using Bode plots approach [22]:

$$W_{Lead-lag}(s) = K_c \left(\frac{1}{\alpha_d} \frac{s + z_{cd}}{s + p_{cd}} \right) \left(\frac{1}{\alpha_i} \frac{s + z_{ci}}{s + p_{ci}} \right), \quad (9)$$

where K_c is a compensator gain, z_{cd} and z_{ci} are zeros, whereas p_{cd} and p_{ci} are poles of lead and lag compensators, respectively, and $\alpha_d = z_{cd} / p_{cd} < 1$ and $\alpha_i = z_{ci} / p_{ci} > 1$.

The closed-loop bandwidth ω_B is set to 7.5 rad/s for fin control loop and to 0.15 rad/s for rudder and yaw control loops and the closed-loop phase margin is selected to be 60°. The digital representations of compensators are ob-

tained by the implementation of Tustin (bilinear) transform:

$$s = \frac{2}{T_s} \frac{z-1}{z+1}, \quad (10)$$

in (9) with T_s denoting sampling time. The parameters of digital lead-lag compensators are presented in Table I.

Table I PARAMETERS OF DIGITAL LEAD-LAG COMPENSATORS

Fin-roll compensator $W_{FRC}(z)$ $T_s = 0.084 \text{ sec}$	$\frac{1086z^2 - 1985z + 905.4}{z^2 - 1.214z + 0.2188}$
Rudder roll stabilization compensator $W_{RRSC}(z)$ $T_s = 4.189 \text{ sec}$	$\frac{3.346z^2 - 3.79z + 0.5583}{z^2 - 1.877z + 0.877}$
Rudder-yaw (ship heading) compensator $W_{RYC}(z)$ $T_s = 4.189 \text{ sec}$	$\frac{-1.387z^2 + 2.298z - 0.9288}{z^2 - 1.595z + 0.5948}$

The parameters of the PID controller are usually determined based on the experience of the operator, trial-and-error method, Ziegler-Nichols method, Bode plots approach or experiments. PID controllers are realized as:

$$W_{PID}(s) = K_p \left(1 + \frac{1}{T_i s} + \frac{T_d s}{1 + \frac{T_d}{N} s} \right), \quad (11)$$

where K_p stands for a proportional gain, T_i for an integrator time constant, T_d for a derivative time constant and N for a derivative filter divisor. The similar Bode plots method as for lead-lag compensators is used in design of the second set of PID controllers. However, the design of PID controller for non-minimum phase rudder-roll dynamics sometimes encounters undesirable responses. That is why, the lead-lag compensator is implemented herein instead of PID controller. The procedure is the same as in the previous case. The parameters of digital PID controllers for fin-roll and rudder-yaw control loops and the digital lead-lag compensator for rudder-roll stabilization are presented in Table II.

Table II PARAMETERS OF DIGITAL PID CONTROLLERS AND LEAD-LAG COMPENSATOR

Fin-roll PID controller $W_{FRC}(z)$ $T_s = 0.084 \text{ sec}$	$\frac{2309z^2 - 3899z + 1616}{z^2 - 0.1204z + 0.8796}$
Rudder roll stabilization compensator $W_{RRSC}(z)$ $T_s = 4.189 \text{ sec}$	$\frac{11.94z^2 + 1.183z - 5.873}{z^2 - 1.206z + 0.2286}$
Rudder-yaw (ship heading) PID controller $W_{RYC}(z)$ $T_s = 4.189 \text{ sec}$	$\frac{-2.256z^2 + 1.982z - 0.1731}{z^2 - 0.01689z + 0.9831}$

Then, a trial-and-error approach, similar to one presented in [13], is used in design of the third set of PID controllers. The controller's natural frequency is chosen first to be equal to a ship's natural frequency. The damping coeffi-

cient that produces the best suitable roll reduction is found using a trial-and-error method. T_i and T_d is calculated then in accordance with $T_d = 1/(2\zeta_d\omega_{nd})$ and $T_i = 1/(2T_d\omega_{nd}^2)$. Lastly, the K_p is gradually raised looking to avoid displacement and rate saturations of the fin and rudder servos. The continuous-time PID controller parameters both with sampling times for Tustin transform are given in Table III.

Table III PARAMETERS OF PID CONTROLLERS

$N=100$	K_p	T_i	T_d	T_s
Fin controller $W_{FC}(s)$	36	1.7244	0.8625	0.263
Rudder roll stabilization controller $W_{RRSC}(s)$	0.4514	1.7244	0.8625	10.3
Yaw (ship heading) controller $W_{YC}(s)$	-0.2	0	6.25	4

IV. SIMULATION RESULTS

Fig. 2 shows the roll alleviation with digital lead-lag compensators in design of fin-roll and rudder-roll control loops. The roll perturbations are also given in the same figure. The simulation results illustrate that the implementation of digital lead-lag compensators gives very good suppression of roll motion. In Fig. 3, the ship course maintaining using digital lead-lag compensators is presented under the yaw perturbations showing fast dynamic response with overshoot, which can be avoided if lag compensator, that cancels the pole of rudder to yaw dynamics, is used as it is done in [21]. The results of implementation of the second set of control algorithms (two digital PID controllers and one lead-lag compensator) in design of roll stabilization system under the action of the identical roll perturbations are given in Fig. 4. The roll reduction is also very satisfactory as in the previous case although the ship course response is not acceptable due to its oscillatory character (Fig. 5). The worst roll motion suppression provides the use of digital PID controller (the third set of control algorithms) tuned by the trial-and-error method (Fig. 6). However, the yaw response is the best in this case since the digital PI controller, that cancels the pole of rudder to yaw dynamics, is implemented (Fig. 7).

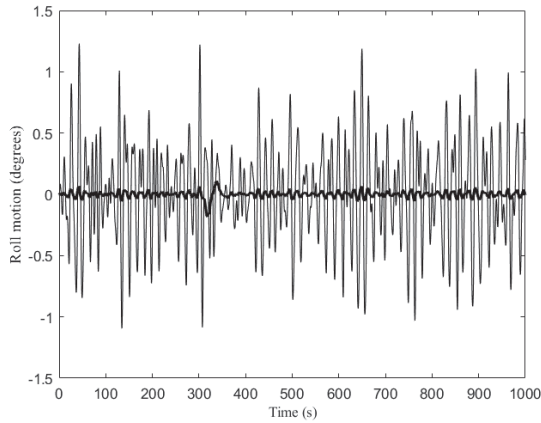


Fig. 2. Roll reduction using digital lead-lag compensators

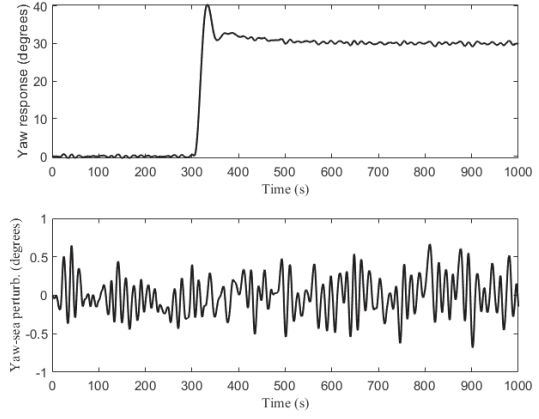


Fig. 3. Yaw (ship direction) control using digital lead-lag compensators

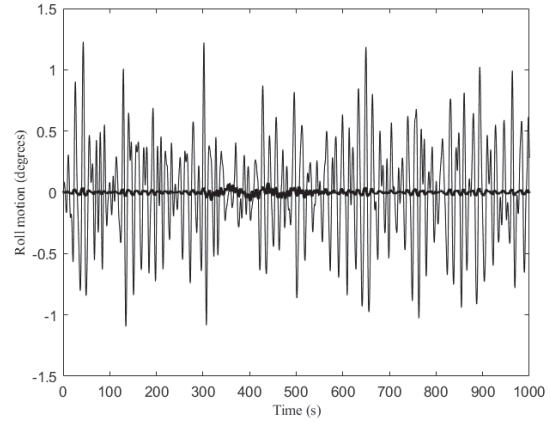


Fig. 4. Roll reduction using two digital PID controllers and one lead-lag compensator

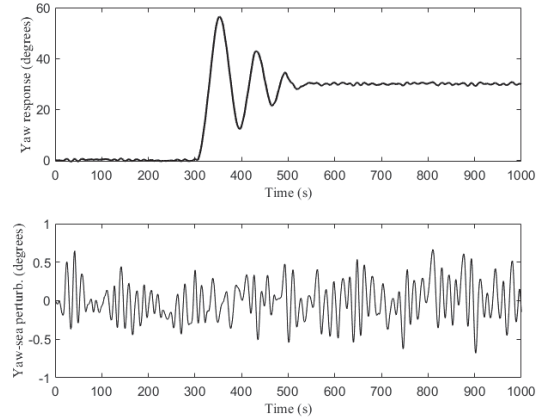


Fig. 5. Yaw (ship direction) control using two digital PID controllers and one lead-lag compensator

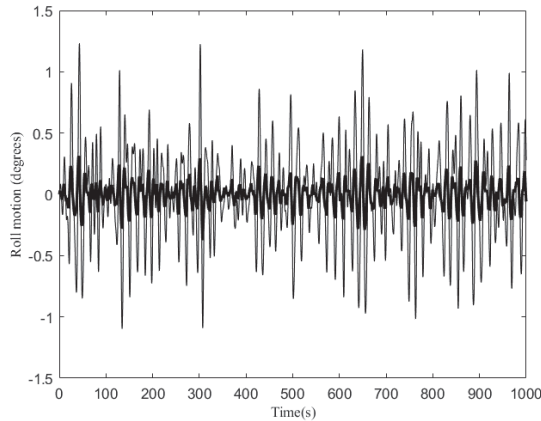


Fig. 6. Roll reduction using PID controllers

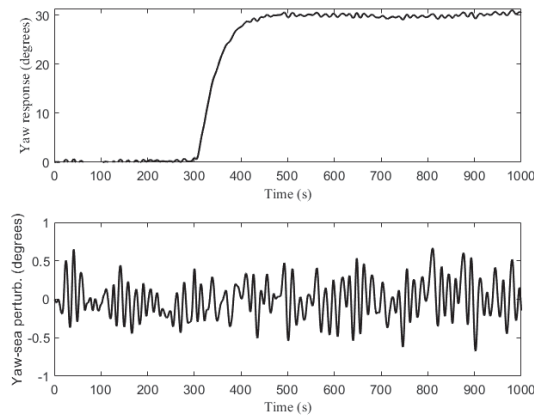


Fig. 7. Yaw (ship direction) control using PID controllers

V. CONCLUSION

There are different active devices helping reduce ship roll motion, and one of them recently most used is an integrated fin rudder roll (INFRR) stabilizer. This paper examines the design of INFRR stabilization system and compares the simulations results of the use of three different controller sets: a set of digital lead-lag compensators created by using Bode plots [22], a set of two digital PID controllers and one lead-lag compensator designed by the same Bode method, as well as a set of PID controllers tuned by the trial-and-error method [12, 13]. Digital simulation results indicate that the lead-lag compensators and PID controllers obtained by Bode plots method offer a little more improved roll reduction in comparison with the implementation of PID controllers adjusted by trial-and-error approaches.

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