SLIDING MODE AND PID CONTROLLERS FOR SHIP ROLL STABILISATION: A COMPARATIVE SIMULATION STUDY

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Abstract: This paper addresses the sliding mode control design for roll reduction of a ship. The sliding mode control (SMC) technique yields the appropriate control with significant roll reduction compared with other controllers such as PID. The system comprises of three different controllers, roll-fin, roll-rudder and autopilot. Therefore, for each situation along the ship trajectory, the triple controllers should be designed. It is not necessary to have the same controller structure for all three subsystems. This paper compares SMC controllers individually with PID controllers for each subsystem, and demonstrates the results of the implementation of controllers with different structures when applied to the entire system.

Keywords: Ship control, Stabilization methods, Sliding mode control, PID controllers, Servomechanisms.

1. INTRODUCTION

The problem of ship stabilisation has widely been studied in the last two decades. Most work has been carried out on stabilisation of the system using classical controllers such as PID and H_2/H_∞ (Fossen, 2002; Katebi, *et al.,* 1997).

Reduction of roll motion is important for the safety on board ship. In addition, roll motion may damage cargo, prevent the crew from working effectively and make passengers uncomfortable. There are various active devices for ship roll reduction including fin-roll (Chadwick, 1955, Fossen, 1995a) or rudder-roll stabilizers (Van Amerongen, 1991), gyroscopes (Sperry, 1915; Perez, 2003), moving weights (Perez, 2003; Lewis, 1989) and activated tanks (Fossen, 1995a, b; Lewis, 1989). Substantial roll reduction may be achieved providing an increase in the speed of the rudder, which is too expensive; however, the use of the rudder to assist fin stabilisers can further improve roll reduction. The control design using a H_2/H_∞ approach for ship models can be found in Katebi, *et al.* (1997) and Roberts *et al.* (1997), and by using various controllers as has been shown in Van Amerongen, (1991) and Perez (2003).

To stabilize the roll of a ship system, various control algorithms have been proposed such as PID (Minorsky, 1947), optimal control (Fossen, 1995b) and H_2/H_∞ (Katebi, *et al.,* 1997).

However, using a (different) triplet of controllers for fin-roll, rudder-roll and autopilot, and particularly the design of a triplet of sliding mode controllers represents a novel approach and is considered in this paper. In fact, previous work has been focused on the same type of controllers for fin-roll, rudder-roll and autopilot. A comparative study using both SMC and PID controllers for each of the subsystems of the ship system is considered here. The results show that the SMC controllers may yield better roll-reduction than PID controllers. A set of different types of controllers may be designed depending on various

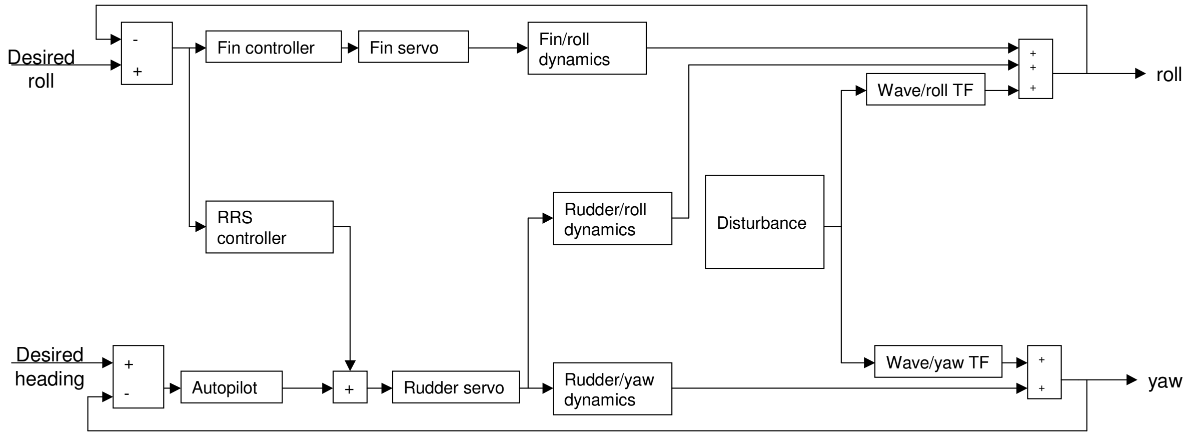

Fig. 1. Block diagram of the ship system.

speeds, environmental and sea conditions so that an appropriate triplet of controllers is selected in correspondence to these conditions.

SMC provides a high frequency switching control signal to force the system trajectories onto a surface, the so-called sliding surface (or sliding hyperplane), after a finite time. Thereafter, the system trajectories tend to the equilibrium point along the sliding surface (Zinober, 1994). The sliding surface is usually designed to achieve the desired specifications. SMC is robust with respect to matched internal and external disturbances. However, undesired chattering produced by the high frequency switching of the discontinuous control may be considered a problem when implementing SMC to some real applications. Many methods including several continuous approximation techniques have been presented to reduce the chattering (Koshkouei and Zinober, 1998).

Some work has been carried out on SMC using the nonlinear state-space representation of a ship's motion (Fossen, 2002). The method in Fossen (2002) differs from the method used in this paper.

In this paper, SMCs are designed for fin-roll, rudder-roll and autopilot systems. In addition, a sliding mode control (or PID control) is designed for fin-roll (rudder-roll) whilst PID and SMC are designed for the second subsystem, rudder-roll (fin-roll) and the third subsystem (autopilot). However, the effectiveness of the controllers depends upon the precise prediction of the sea wave and environmental conditions.

Sea perturbation is usually modelled by filtering white noise. This model describes the ship's behaviour at a given speed in a steady sea state. Fig. 1 shows a ship system representation combined with a sea perturbation model.

Stabilising fins are the most effective and the most popular devices for roll reduction. They are typically used for high-speed vessels such as warships and cruise ships. Lift forces (that depend on the angle of the fins) are generated by the fins and a couple is produced to counteract the wave-induced roll moment. However, since the lift force depends upon the relative inflow speed, fin-roll stabilisation is only effective when the ships are travelling at relatively high speeds.

Some work has been focused on roll-rudder stabilisation (Van Amerongen, 1991). In fact, substantial roll reduction may be achieved using the rudder. In this case, the rudder rate has to be as high as 10-15deg/sec. This is considerably faster than most attainable rudder rates aboard ships, where 3 deg/sec is a typical value. However, the rudder is used to assist the fin stabilisers for further improvement of roll reduction. It should be noted that the rudder's primary purpose is altering course. However, one has to question whether it is possible to reduce roll and alter course at the same time whilst using the rudder. From a heading control point of view, compensating for low frequency yaw motions is the main concern and requires slower movements of the rudder than those generally required for roll reduction. It will therefore be assumed that there is a frequency separation between the bandwidth of the rudder-roll control system and the bandwidth of the heading control system and that interferences between the two systems can be neglected. This implies that the autopilot and the rudder-roll controller can be designed separately. Nevertheless, after the design of the two controllers, it will be necessary to check whether the interferences between the two controllers can be neglected in practice.

In this paper, a ship model which describes the behaviour at a given speed and in given sea conditions, is considered. Sets of different controller types are designed, evaluated and compared in simulation. The objective is to achieve the best roll reduction, whilst controlling the heading of the ship in this specific situation.

This paper is organised as follows: In section 2 the ship model, PID, and SMC controllers are considered. In Section 3, roll reduction using various controllers and control of the entire ship model are addressed. Simulation results are presented in Section 4. Conclusions are presented in Section 5.

2. SHIP MODEL AND CONTROL DESIGN

A ship control system consists of three subsystems: fin-roll dynamics, rudder-roll dynamics and rudder-yaw dynamics (see Fig. 1). The system is nonlinear, however, a linear approximation is used to simplify the model.

The fin-roll, rudder-roll, rudder-yaw dynamics transfer functions are $G_{fin-roll}(s)$, $G_{rudder-roll}(s)$ and $G_{rudder-yaw}(s)$, respectively,

$$G_{fin-roll}(s) = \frac{0.02652(s+1)}{s^2 + 0.2638s + 0.6702}$$

$$G_{rudder-roll}(s) = \frac{-0.42248s + 0.10562}{6s^3 + 2.5828s^2 + 4.285s + 0.6702}$$

$$G_{rudder-yaw}(s) = \frac{-0.09928}{s(6.25s+1)}$$

2.1. *Control design*

In this section, two different types of controllers, PID and SMC, for stabilising the ship's motion are designed. Since there are three subsystems in the overall system, and each subsystem can be controlled with PID and SMC controllers, it follows that six different triple controllers are required. The performances of these controllers are then compared.

2.2 *PID Controllers*

The transfer function of a PID controller is given by

$$K(s) = K_P(1 + \frac{1}{T_I s} + T_D s)$$

where K_P, $1/T_I$ and T_D represent the proportional, the integral and the derivative actions of the controller, respectively.

The procedure for tuning a PID controller is as follows: The natural frequency of the controller is first selected (in this case the natural frequency of the ship is used). Then using a 'trial and error' method, the damping coefficient, which yields the most appropriate roll reduction, is determined. Finally, K_P is increased until rate and displacement saturations appear in the fin servos (De Larminat, 1993).

2.3 *Sliding mode controllers*

In this section, the design method for the sliding mode controllers for the fin-roll, rudder-roll and rudder-yaw subsystems are described.

Consider the system

$$\dot{x} = Ax + Bu$$

where $x \in R^n$ is the state, u is the scalar control input, $A \in R^{n\times n}$ and $B \in R^{n\times 1}$. Define the sliding function as $\sigma = Cx$ where $C \in R^{1\times n}$. The sliding mode control

$$u = u_l + u_n = -(CB)^{-1}\left(CAx + K\,\mathrm{sgn}(\sigma)\right)$$

with *K>0,* forces the system trajectories onto a sliding surface in a finite time and guarantees the trajectories remain on it thereafter.

A drawback of SMC is the chattering resulting from a discontinuous control. There are many methods to reduce chattering including continuous approximations. One can consider the following continuous approximation for the nonlinear term of the control

$$u_n = -K\frac{\sigma}{|\sigma| + \delta}, \qquad 0 < \delta < 1$$

(Zinober, 1994). Another suitable continuous approximation is

$$u_n = -K\begin{cases} 1 & \text{if } \ \sigma > \varepsilon \\ f(\sigma) & \text{if } |\sigma| \le \varepsilon \\ -1 & \text{if } \ \sigma < \varepsilon \end{cases}$$

where ε is a small positive real number and $f(\sigma)$ is a continuous function crossing the origin and points $(\pm\varepsilon, \pm 1)$ (Koshkouei and Zinober, 1998; Zinober, 1994). A simple and suitable choice is $f(s) = \dfrac{\sigma}{\varepsilon}$.

3. CONTROL OF THE ENTIRE SHIP MODEL

In this section, the control of the entire ship model is considered. Six different triple controllers are compared and evaluated. The expression 'triple controller' refers to the choice of a controller for each subsystem (fin-roll, rudder-roll and rudder-yaw). Since the entire ship model can be decomposed into three subsystems (fin-roll, rudder-roll and rudder-yaw), the term triple is used.

3.1 Assessing the performance of the triple controllers

To assess the performance of a triple controller for the entire ship model, the following points regarding the capability of the controller are required to be considered:

- reduce roll motions during a steady course and a change of course;
- maintain a steady course (autopilot);
- change course rapidly and smoothly; and
- avoid rate and displacement saturations in the ship's servomechanisms.

To assess the performances of the controllers on the fin-roll and rudder-roll subsystems, the roll reduction percentage (RRP) is considered. The RRP is defined as follows:

$$PRP = \frac{\sqrt{|\mathrm{var}(\text{Roll perturbation})|} - \sqrt{|\mathrm{var}(\text{Roll angle})|}}{\sqrt{|\mathrm{var}(\text{Roll perturbation})|}} \times 100\%$$

The percentage of roll reduction achieved for fin- and rudder-roll models with various controllers are shown in Tables 1 and 2, respectively. In Tables 1 and 2, FRC, RRC and RYC stand for the fin-roll controller, the rudder-roll controller and the rudder-yaw controller (autopilot), respectively.

Table 1. Implementation of different controllers for subsystems

Controller	FRC	RRC	RYC
1	PID	PID	PID
2	PID	PID	SMC
3	PID	SMC	PID
4	SMC	SMC	SMC
5	SMC	PID	PID
6	SMC	PID	SMC

Table 2. Roll reduction percentage achieved by the different controllers

Controller	Global	FRC	FRC	RYC
1	63.4	61.4	65.1	62.4
2	65.5	62.3	67.5	68.3
3	76.5	74.5	73.2	80.8
4	79.5	86.3	75.6	85.0
5	78.2	83.7	75.6	81.5
6	82.9	87.6	80.6	86.5

4. SIMULATION RESULTS

Figs. 2 and 3 show the roll and yaw perturbation signals used throughout the different simulations and the power spectral density (PSD) of these signals.

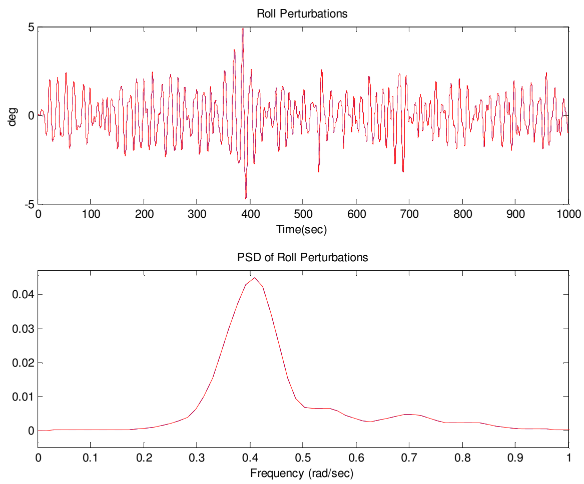

Fig. 2. The roll perturbation signal and its PSD

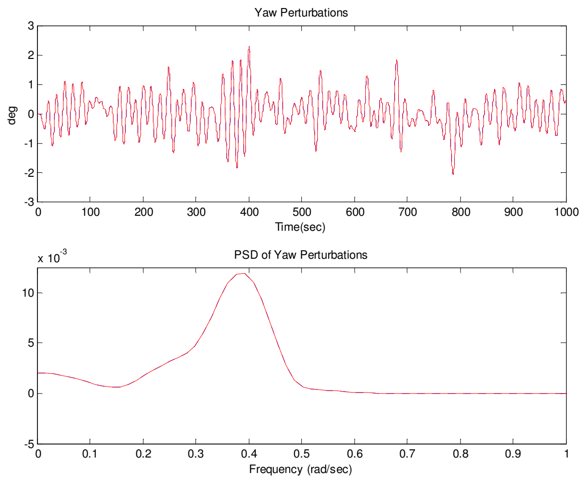

Fig. 3. The yaw perturbation signal and its PSD.

Table 1 shows the PID and SMC controllers which have been implemented to fin-roll, rudder-roll and rudder-yaw (autopilot) models. For all cases, a pre-compensator for the autopilot system is designed to smooth the desired heading signal, which is a step signal of about 30 degree. Table 2 illustrates the roll reduction percentage resulting from each controller over the ship trajectory (1000 seconds) and each different phase of the simulation (see Figs. 4-7).

Phases 1, 2 and 3 indicate the course keeping at 0 degree, course changing from 0 degree to 30 degree and course keeping at 30 degrees, respectively.

Amongst the initial three triple controllers, the particular combination, i.e. the triple controllers 6 (see Table 2) yields the best results since it produces the largest roll reduction rate (see Fig. 6). However, during phase 2, this controller is slower than the PID controller (see Figs. 4-7). Furthermore, at T=400 seconds, the amplitude of the roll perturbations is large and suddenly influences the roll reduction. At this point, there are repeated rate saturations in the fin servos (see Fig. 6). Nevertheless, since the sliding mode fin-roll controller provides significant results from the roll reduction percentage point of view in phases 1 and 3, the roll-fin sliding mode controller is retained. Therefore, SMC for fin-roll is used and investigated to find PID or SMC controllers for the other subsystems.

PID controllers for roll-rudder model yield a significant roll reduction percentage. In this case, there are also occasional saturations in the servos. However, the resulting capability for maintaining a steady course is not as good as SMC (see Figs. 6 and 7). Low frequency waves also appear during phase 1 and phase 3.

Suitable results are obtained with the controllers 6 (SMC-PID-SMC) and 4 (SMC-SMC-SMC). See Figs. 5 and 6. In fact, roll reduction is acceptable and the number of rate or displacement saturations in the servos is small. However, from simulation, it is clear that the controller 6 performs better than the controller 4 during phase 2, whilst during phases 1 and 3, the controller 6 seems to slightly amplify the yaw disturbances. To remove this, controller 4 may be applied during a steady course and this could then be switched to controller 6 when changing a course.

Roll perturbation is generated by the system comprising of the sea state model and a modified form of the ship's roll dynamics. In the same way, yaw perturbation is generated by a system comprising the sea state model and the ship's yaw dynamics. Both roll and yaw perturbations are modelled as an output perturbation.

5. CONCLUSIONS

Six different triple controllers for a ship's model have been compared. Compromises are required to be made between roll-reduction percentage, maintaining a steady course and changing course. From a general point of view, controllers 4 and 6 yield the best overall performances. An interesting solution would be to use a controller during a steady course and to switch to another controller during course changes.

In this paper, it has been assumed that the ship has had a constant speed and the sea state remains fixed for a certain period of time. However, in reality, the sea wave and environmental conditions often vary and these variations affect the system. The fin-roll, rudder-roll and rudder-yaw (autopilot) dynamics and the entire system has been stabilised via PID and SMC controllers. The most suitable controllers for fin-roll, rudder-roll and rudder-yaw are sliding mode for roll-fin, PID for roll-rudder and PID or SMC for autopilot, respectively. However, when the sea conditions change, these results may not necessarily be valid. Therefore, for each sea condition and speed, one of these controllers may reduce the roll effectiveness on the ship's motion.

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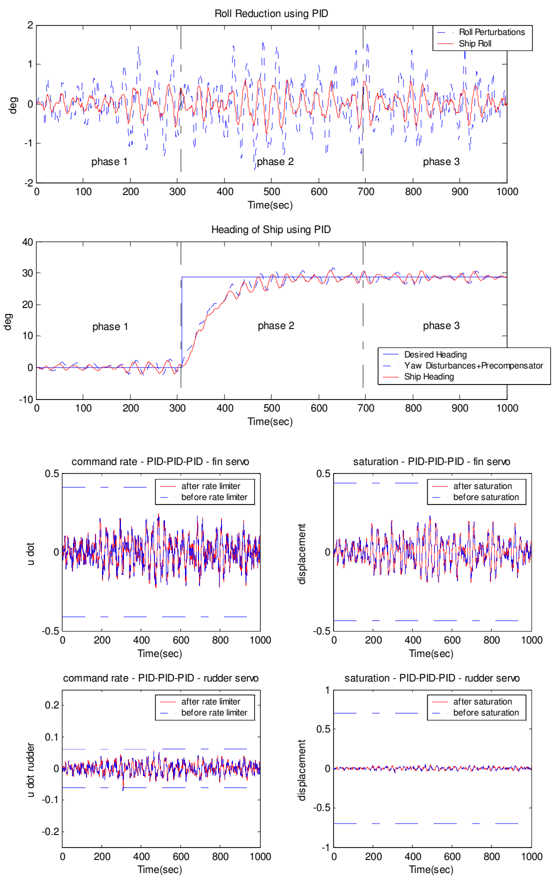

Fig. 4. The responses of the system with the triple controllers 1, PID-PID-PID.

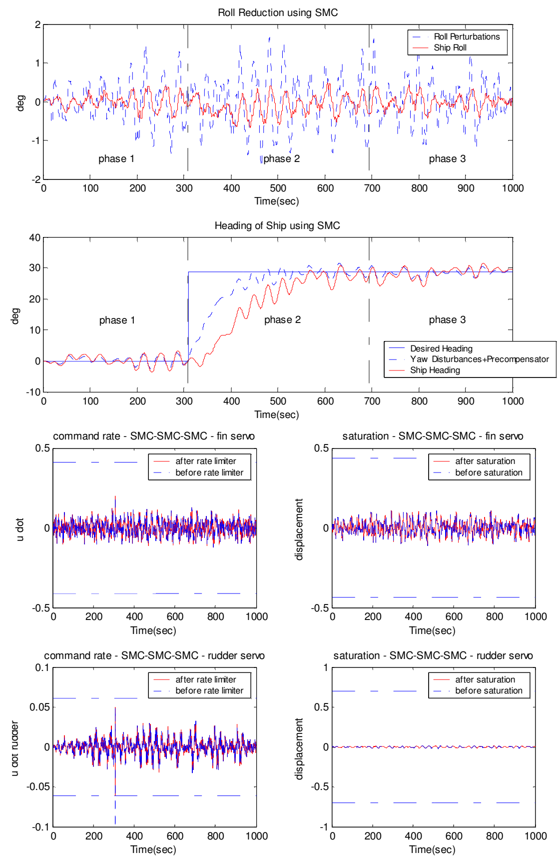

Fig. 5. The responses of the system with the triple controllers 4, SMC-SMC-SMC.

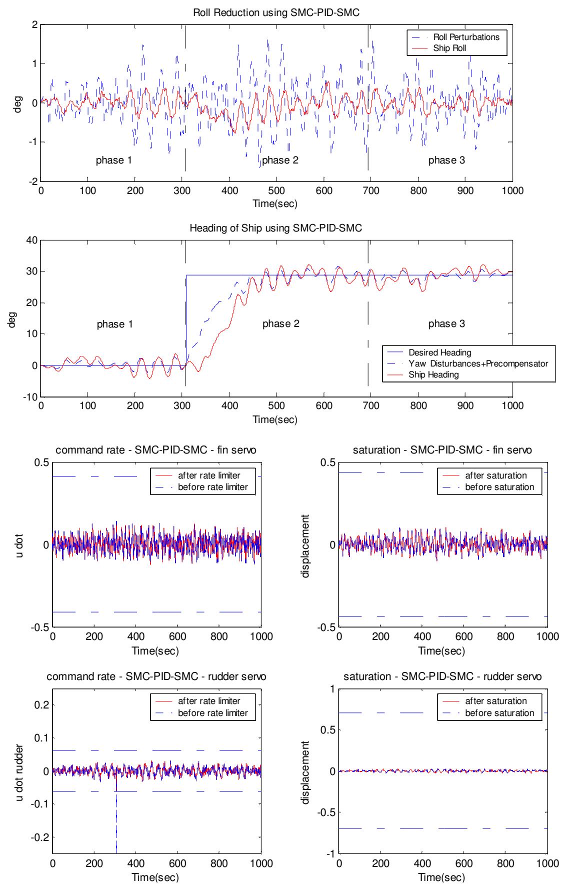

Fig. 6. The responses of the system with the triple controllers 6, SMC-PID-SMC.

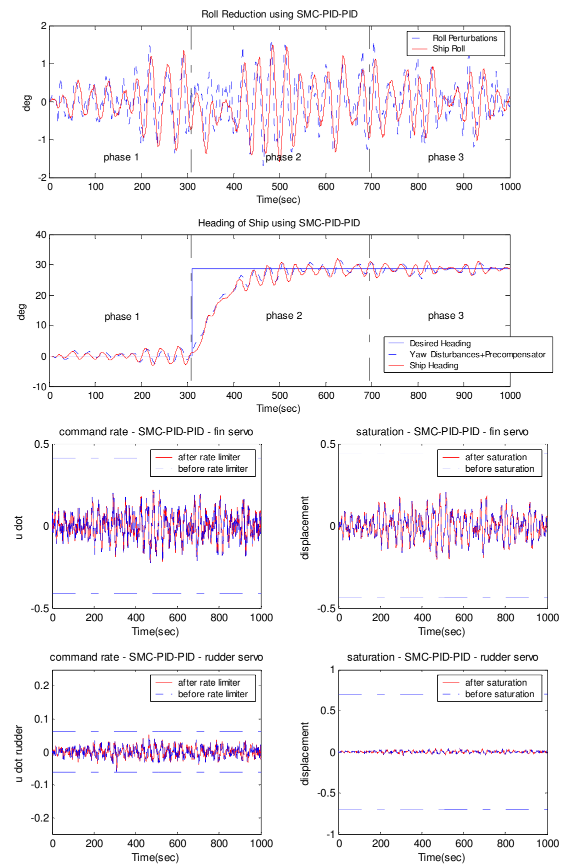

Fig. 7. The responses of the system with the triple controllers 5, SMC-PID-PID.