J. Automation & Systems Engineering 7-3 (2013): 94-104

Journal of Automation
& Systems Engineering

Regular paper

Robust Rudder Roll Reduction of Container Ship

H. Saari[1] and E. Khichane[2]

***Abstract-** The aim of this paper is to apply the H_∞ control on the container ship in order to reduce the roll effect and to stabilize its yaw using the rudder. The main difficulty is to determine an admissible control law for the actuator in a way that it does not reach its saturation limit. The new idea presented in this paper is to introduce the disturbance model in the design of the control law. A cascade control structure is developed using $H\infty$ control to compute the controller by taking into account the real condition of navigation. Some simulation results illustrate the performance of this method.*

Keywords: Ship control, linear control, robust control, roll stabilization.

1 INTRODUCTION

The increase in the sea traffic and the development of technologies required the use of the increasingly large and modern ships. Consequently the traditional techniques of control became obsolete considering the complexity of these ships. To ensure their effective control and consequently safety of the passengers and the goods, new control system should be developed.

Automatic control strategies for marine vehicles are in general designed to improve their functions with adequate reliability and economy. The main purpose of the rudder is to control the heading of the ship in course-keeping and course-changing maneuvers [1]. Applying more sophisticated autopilots for ship steering is mainly due to performance improvement and fuel economy [2].

Since the ship is always sailing in the seaway, the wave disturbances will affect the ship motions, especially on the roll motion. Large roll motion may cause cargo damage and reduce the effectiveness of crews because of seasickness and tiredness. For some ships, landing a helicopter will become more difficult when the roll motion is too large.

The worst situation is if the ship is unable to counteract the large roll motion, the operation may be suspended and may lead the capsizing. In a word, the serious roll motion generally affects the ship stability, comfort and efficiency of screws, accuracy of electrical mechanism, and ship course. Therefore reducing roll motion is advantageous for ships in waves.

Some devices have been well employed to accomplish roll reduction, e.g. bilge keels, anti-roll tanks, gyroscopic stabilizers, moving weights, and stabilizing fins [3]. Although most of the devices work well, additional devices and external power installations will lead to the weight increase and space decrease on the ship. The hydrodynamic stability and structural strength may be changed when the anti-roll tanks are adopted. The installation

---

[1] Corresponding author
[1, 2] SETRAM, Ecole Nationale Supérieure Maritime BP. 61, 42415 Bou-Ismail, Algeria
(Hammoud.saari, hacenekhichane)@yahoo.fr

cost is also generally raised and the ship speed may be decreased because of additional appendages.

Usually most ships use rudder to alter the course and it is known that the rudder action will cause some roll motion even in calm water. It means the rudder can produce an additional roll moment and therefore can then be regarded as a roll reduction device if the ship's course is not violently altered. The roll reduction using the rudder control technique has been proposed for two ships doing underway replenishment [4] and for a single ship sailing in waves.

Our work deals with the use of a rudder control system in order to minimize the rolling effect and at the same time, to monitor the course of a container ship. For this purpose, an H_∞ control has been chosen, with a cascade structure, regarding to its ability to achieve our goals in spite of disturbances. In our case these disturbances are characterized by the state of the sea (waves are characterized by their height and period), which is constantly changing. These changes are classified as: calm sea, smooth, slight, moderate, rough...

This paper is divided into three sections. The first one presents the ship modeling. The study of the vessel motion will be conducted first in order to deduce its nonlinear model. Since the nonlinearity is difficult to be used for the control law computing, a linear model imposes itself. Afterwards, one shows the modeling of the rudder which is the main actuator as well as the modeling of waves that are the main disturbances. In section 3, the problem of the synthesis of the H_∞ control is presented and it is followed by some simulation results.

2 SHIP MODELING

The environment in which a ship is moving is very variable depending on weather conditions, seasons and geographical locations. All these changes in the environment of the vessel have an important influence on its motion and its behavior. Therefore, the study of the ship motion is very complex. Obtaining a reliable model requires the determination of a set of parameters that interfere with its dynamics.

Several researches have been performed on the ship modeling domain [1, 2, 4, 5, 6 and 7]. In [8], we can find that in 1975, Abkowitz described the ship motion with four degrees of freedom. Son and Nomoto in 1982 presented a model obtained by combining planar motion mechanism test data for lateral motion, using different values of static heel for model under test with independent roll motion tests. Another model was presented by Kälström and Otterson in 1983. It combined a lateral planar motion mechanism model with theoretical estimates of roll coefficients using free sailing model tests to calibrate the roll parameters.

In this section, a model based on experimental results is presented in the unique 4-DOF, developed by the Danish maritime institute [8] that allows model testing with full dynamic interaction between motions in roll, sway, yaw and surge. The model has also been subject to validation via full-scale sea trials [3].

2.1. Non linear model of the ship

In this paper the SNAME conventions (Society of Naval Architects and Marine Engineers) [9] is adopted. The motion of a ship in six degrees of freedom is considered as a translated motion (position) in three directions: surge, sway and heave, and as a rotation motion (orientation) about three axes: roll, pitch and yaw. To determine the equations of motion, two reference frames are considered: the inertial or the fixed to earth frame $Oxyz$ that may be taken to coincide with the ship-fixed coordinates in some initial condition and the body-fixed frame $O_0x_0y_0z_0$ (Figure 1). For surface ships, the most commonly adopted position for body-fixed frame which gives hull symmetry about the $O_0x_0z_0$ plane and approximate symmetry about $O_0y_0z_0$ plane while the origin of the z_0 axis, is defined by the calm water surface.

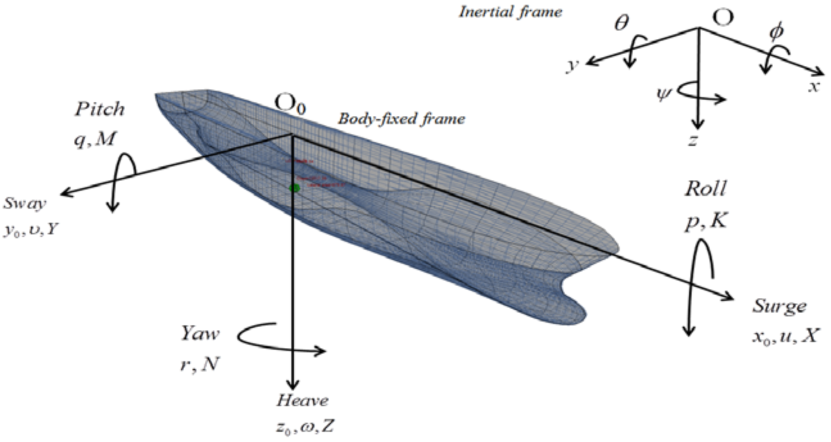

Figure 1. Ship motion description.

The Newtonian approach gives the equations of vehicle in the body-fixed frame and considers that motions in pitch and heave can generally be neglected in comparison with the other motions for conventional surface ships. Thus, ship motion modeling can be considered only with 4-DOF: surge, sway, yaw and roll. The following approximations are set up:

$$\dot{\varphi} = p \tag{1}$$

$$\dot{\psi} = r\cos(\varphi) \tag{2}$$

$$\begin{bmatrix} m & 0 & 0 & 0 \\ 0 & m & -mz_G & mx_G \\ 0 & -mz_G & I_{xx} & 0 \\ 0 & mx_G & 0 & I_{zz} \end{bmatrix} \begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{p} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} X \\ Y \\ K \\ N \end{bmatrix} + \begin{bmatrix} m(vr + x_G r^2 - z_G pr) \\ -mur \\ mz_G ur \\ -mx_G ur \end{bmatrix} \tag{3}$$

where m is the mass of the ship, I_{xx} and I_{zz} are the inertias about the x_0 and z_0 axes. x_G and z_G are the coordinates of the center of gravity CG with respect to the body-fixed frame, i.e., $\overline{CG} = [x_G \quad 0 \quad \mathrm{z_G}]^{\mathrm{T}}$.

X, Y, K and *N* denote respectively the hydrodynamic forces and moment and also the forces and moment due to the rudder acting on the hull.

The hydrodynamic forces result from the movement of the ship on the surface of the water. They not only depend on the speed, the weight and the profile of the hull but also on the effect of waves. The structure of these forces and moments is shown in equations (6) to (9). The results are given as non dimensional quantities using *the prime system* [8]. In this model, the non-dimensional relative surge speed

$$u'_a = \frac{U - U_{nom}}{U} \tag{4}$$

is used in hydrodynamic terms, where U is the ship absolute speed presented by the following equation:

$$U = \sqrt{u^2 + v^2} \tag{5}$$

It should be noted that u'_a is different from non-dimensional surge velocity $u' = u / U$.

The non-dimensional surge equation is:

$$\begin{aligned} X_{hyd} &= X_{\dot{u}}\dot{u}'_a + X_u u'_a + X_{uu} u'^2_a + X_{uuu} u'^3_a + X_{vr} v' r' + X_{rr} r'^2 + X_v v' + X_{vv} v'^2 + X_{v\varphi} v' \varphi' + + X_{\varphi} \varphi' \\ &\quad + X_{\varphi\varphi} \varphi'^2 + X_{pp} p'^2 + X_{ppu} p'^2 u'_a \end{aligned} \tag{6}$$

The non-dimensional sway equation is:

$$\begin{aligned} Y_{hyd} &= Y_{\dot{v}} \dot{v}' + Y_{\dot{r}} \dot{r}' + Y_{\dot{p}} \dot{p} + Y_v v' + Y_{vv} v'^2 + Y_{v|v|} v'|v'| + Y_{v|r|} v'|r'| + Y_{vrr} v' r'^2 + Y_r r' + Y_{r|r|} r'|r'| + Y_{rrr} r'^3 \\ &\quad + Y_{r|v|} r'|v'| + Y_{rvv} r' v'^2 + Y_p p' + Y_{ppp} p'^3 + Y_{pu} p' u'_a + Y_{pu|pu|} p' u'_a |p' u'_a| \\ &\quad + Y_{\varphi} \varphi' + Y_{v\varphi} v' \varphi' + Y_{v\varphi\varphi} v' \varphi'^2 + Y_{\varphi vv} \varphi' v'^2 + Y_0 + Y_{0u} u'_a \end{aligned} \tag{7}$$

The non-dimensional roll equation is:

$$\begin{aligned} K_{hyd} &= K_{\dot{p}} \dot{p} + K_{\dot{v}} \dot{v}' + K_{\dot{r}} \dot{r}' + K_v v' + K_{vv} v'^2 + K_{v|v|} v'|v'| + K_{v|r|} v'|r'| + K_{vrr} v' r'^2 + K_{r|r|} r'|r'| + K_{rrr} r'^3 \\ &\quad + K_{rvv} r' v'^2 + K_{r|v|} r'|v'| + K_p p' + + K_{p|p|} p'|p'| + K_{ppp} p'^3 + K_{pu} p' u'_a + K_{pu|pu|} p' u'_a |p' u'_a| \\ &\quad + K_{v\varphi} v' \varphi' + K_{v\varphi\varphi} v' \varphi'^2 + K_{\varphi vv} \varphi' v'^2 + K_0 + K_{0u} u'_a + K_r r' - (\rho \, g \, \nabla \, \mathrm{G}_Z(\varphi))' \end{aligned} \tag{8}$$

and the non-dimensional yaw equation is:

$$\begin{aligned} N_{hyd} &= N_{\dot{v}} \dot{v}' + N_{\dot{r}} \dot{r}' + N_{\dot{p}} \dot{p} + N_v v' + N_{vv} v'^2 + N_{v|v|} v'|v'| + N_{v|r|} v'|r'| + N_{vrr} v' r'^2 + N_r r' + N_{r|r|} r'|r'| + N_{rrr} r'^3 \\ &\quad + N_{r|v|} r'|v'| + N_{rvv} r' v'^2 + N_p p' + N_{ppp} p'^3 + N_{pu} p' u'_a + N_{pu|pu|} p' u'_a |p' u'_a| \\ &\quad + N_{\varphi} \varphi' + N_{v\varphi} v' \varphi' + N_{v\varphi\varphi} v' \varphi'^2 + N_{\varphi vv} \varphi' v'^2 + N_0 + N_{0u} u'_a \end{aligned} \tag{9}$$

The last term of (8) corresponds to the restoring roll moment in which ∇ denotes the ship displacement, g is the constant gravity, ρ is the masse density of the water and $G_Z(\varphi)$ is the buoyancy for heel that can be approximated as [3]:

$$G_Z(\varphi) = \left(GM + \frac{1}{2} BM \tan^2(\varphi) \right) \sin(\varphi) \tag{10}$$

where *GM* is the metacenter height, and *BM* is the distance from the center of buoyancy to the metacenter.

The forces and moment due to the rudder acting on the hull are given by:

$$X_{rudder} = X_{\delta} \delta' + X_{\delta\delta} \delta'^2 + X_{\delta u} \delta' u'_a + X_{\delta\delta u} \delta'^2 u'_a + X_{v\delta} v' \delta' + X_{v\delta\delta} v' \delta'^2 \tag{11}$$

$$Y_{rudder} = Y_{\delta} \delta' + Y_{\delta\delta} \delta'^2 + Y_{\delta\delta\delta} \delta'^3 + Y_{\delta v} \delta' v' + Y_{\delta vv} \delta' v'^2 + Y_{\delta u} \delta' u'_a + Y_{\delta\delta u} \delta'^2 u'_a + Y_{\delta\delta\delta u} \delta'^3 u'_a \tag{12}$$

$$K_{rudder} = K_{\delta} \delta' + K_{\delta\delta} \delta'^2 + K_{\delta\delta\delta} \delta'^3 + K_{\delta v} \delta' v' + K_{\delta vv} \delta' v'^2 + K_{\delta u} \delta' u'_a + K_{\delta\delta u} \delta'^2 u'_a + K_{\delta\delta\delta u} \delta'^3 u'_a \tag{13}$$

$$N_{rudder} = N_{\delta} \delta' + N_{\delta\delta} \delta'^2 + N_{\delta\delta\delta} \delta'^3 + N_{\delta v} \delta' v' + N_{\delta vv} \delta' v'^2 + N_{\delta u} \delta' u'_a + N_{\delta\delta u} \delta'^2 u'_a + N_{\delta\delta\delta u} \delta'^3 u'_a \tag{14}$$

2.2. Linear ship model

The full nonlinear model is too complex to be used for designing the controller, so a linear model is chosen. It is easily obtained from equations (1) to (3) with hydrodynamic effects in non-dimensional forms (6)-(14).

It is a common practice to uncouple the surge equation from the others to analyze the linearized model. Thus, we consider a given service speed $\bar{u}$ and the reduced state vector $z = \begin{bmatrix} v & r & p & \varphi & \psi \end{bmatrix}^T$. The linearized model is obtained at $\bar{z} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T$ and $\bar{\delta} = 0$ as:

$$\dot{z} = H^{-1}F \;\; z + H^{-1}G \;\; \delta \tag{15}$$

where

$$F = \begin{bmatrix} Y_v & (Y_p + Y_{pu}u'_a) & (Y_r - mu') & Y_\phi & 0 \\ K_v & (K_p + K_{pu}u'_a) & (K_r + mz_G\bar{u}') & -(\rho g \nabla GM) & 0 \\ N_v & (N_p + N_{pu}u'_a) & (N_r - mx_G\bar{u}') & N_\phi & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \end{bmatrix}$$

$$H = \begin{bmatrix} (m - Y_{\dot{v}}) & -(mz_G + Y_{\dot{p}}) & (mx_G - Y_{\dot{r}}) & 0 & 0 \\ -(mz_G + K_{\dot{v}}) & (I_{xx} - K_{\dot{p}}) & -K_{\dot{r}} & 0 & 0 \\ (mx_G - N_{\dot{v}}) & -N_{\dot{p}} & (I_{zz} - N_{\dot{r}}) & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$G = \begin{bmatrix} Y_\delta & K_\delta & N_\delta & 0 & 0 \end{bmatrix}^T$$

2.3. Model of Steering Machine

The rudder is the main actuator in the control scheme. The mathematical model of the rudder mechanism most commonly used in computer simulations and autopilot design, is presented by a simplified model in [2]. In Figure 2, a block diagram representation of this model is seen. It contains two limiters, one describing the limitation of the rudder angle and the other describing the limitation of the rudder speed. The rudder limit is determined either by the rudder-angle constraints of the autopilot, or by the mechanical constraints. The maximum rudder speed is determined by the maximum valve opening and the pump capacity of the steering machine.

The SOLAS convention (International Convention for the Safety of Life at Sea, Chapter II part C, Regulation 29.3.2) request that the steering gear is "capable of putting the rudder over from 35° on one side to 35° on the other side with the ship at its deepest seagoing draught and running ahead at maximum ahead service speed in not more than 28 seconds" [10]. A maximum rudder speed of as low as 2.5 degrees per second is sufficient to meet this requirement.

Many researchers have shown that the rudder speed of 5-20 (deg/s) is usually required for a rudder roll damping system to work properly [1].

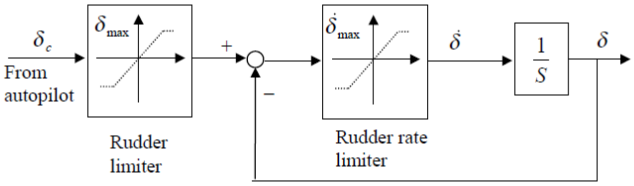

Figure 2. Simplified block diagram of the steering machine model.

2.4. Wave Model

Wave, wind and current are the main factors causing disturbances to a ship on the sea. Considering ship rolling, wave is the most important disturbance.

In order to simplify the design of a control system, a linear model proposed by the ISSC (International Ship and offshore Structures Congress) is used to replace the nonlinear complex wave model [3]. It is a white noise which is filtered by the transfer function:

$$h(s) = \frac{K_v s}{s^2 + 2\zeta\omega_0 s + \omega_0^2} \tag{16}$$

The parameters values are obtained from Table 1, where $h_{1/3}$ is the significant wave height (the average height of the largest third of the waves) and T_w is the average wave period.

Table 1. Wave parameters

Symbol	Signification	Value
ζ	Damping coefficient	0.3
σ_w	Wave intensity	$\sigma_w = \sqrt{0.0185 T_w} h_{1/3}$
ω_0	Dominating wave frequency	$\omega_0 = 4.85 / T_w$

The gain is given by $K_w = 2\zeta\omega_0\sigma_w$.

In section 4, we are going to put ourselves in two working conditions, namely a slight sea (sea state 3) and a moderate sea (sea state 4). Below the sea state 3, the sea is considered as beautiful and consequently the control of the ship does not raise major problem. Beyond the sea state 4, the sea is strong; the control of the ship becomes relatively difficult. Indeed, since the rudder is used to control the course, it can be dangerous to use it for the roll stabilization.

3 H_∞ CONTOL SYNTESIS

The effect of the sea wave on ship could be considered as an external disturbance added to the output of the system.

Using the well known Mixed-Sensitivity approach of robust control design (Figure 3), the problem is to specify suitable functions $W_1(s)$ for the sensitivity function and $W_3(s)$ for the complementary sensitivity function [11].

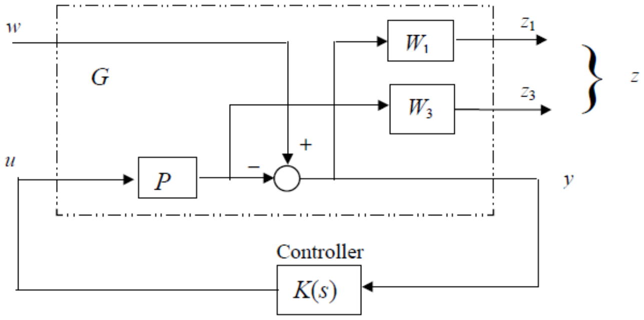

Figure 3. Mixed sensitivity problem.

In the mixed-sensitivity problem formulation, nominal disturbance reduction and stability margin specifications are combined into a single infinity norm of the form [3]:

$$\left\| \begin{matrix} W_1 S \\ W_3 T \end{matrix} \right\|_\infty \leq 1 \tag{17}$$

S and T are respectively the sensitivity and the complementary sensitivity functions.

When the main objective is to reject the disturbance d, it will be judicious to take into account the range of frequency in which d excites the output of the system. Thus, the disturbance could be shown by the form:

$$d = W_d(s) \cdot d' \tag{18}$$

where $d'(j\omega)$ is a unit white noise and $W_d(s)$ permit to give a particular specter to d. In our case, $W_d(s)$ is equal to the linear wave model (16). The following problem is resolved like:

$$\left\| W_1 S W_d \right\| < 1 \tag{19}$$

$$\left\| W_3 T W_d \right\| < 1 \tag{20}$$

W_1 and W_3 bounds respectively the frequency shape of the sensitivity function S filtered by W_d and of the complementary sensitivity T filtered by W_d. W_1 is a low pass filter and W_3 is a high pass filter. The synthesis of both filters can be made by defining specifications which are translated by constraints on their gain.

Assume the following specifications [10]:

Good rejection of disturbances

Good track of ship heading (course keeping)

Response without static error.

Since the ship is a Single-Input (rudder angle δ) Muti-Output (roll φ and yaw ψ) plant, many design schemes may be used to obtain the rudder roll damping controller. One scheme is to design two controllers for course keeping and roll damping respectively. This method will simplify the problem by first considering the heading control only, and then regard the heading loop as an inner loop to design roll damping controller. There are two ways to realize the design; one way is to put the outputs of the two controllers together, and the two controllers are linked with parallel connection, which is called parallel control structure [10]. The other way is to connect the output of roll controller to the input of heading controller. These two controllers are in the form of series connection, which is called cascade control structure [3]. In this paper, we are interested to this last structure by taking into account the disturbances model (16) in the controller synthesis [12].

We will design a course keeping controller only (the inside of dash line in Figure 4) and then close the course keeping loop to design the roll controller. Note that, the model of steering machine is included in the ship model, as a 1st order dynamic block.

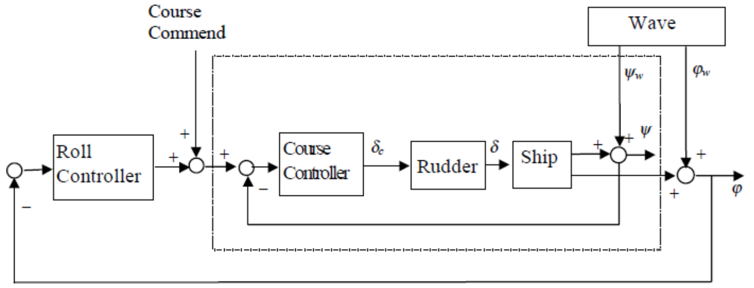

Figure 4. The structure of cascade control.

3.1. Course keeping controller

The weight function W_1 will be a low-pass filter and W_3 will be a high-pass filter. An appropriate choice of these two functions [12]:

$$W_1(s) = \frac{3s + 6.568}{4s + 0.001} \tag{21}$$

$$W_3(s) = \frac{s + 0.01}{0.1 + 1.568} \tag{22}$$

satisfies the robustness conditions (19) and (20) like shown in Figure 5 and Figure 6.

3.2. Rolling controller

The choice of weight functions respecting the robustness condition (19) and (20) like shown in Figure 7 and Figure 8 is [12]:

$$W_1(s) = \frac{75s + 66.14}{100s + 0.6614} \tag{23}$$

$$W_3(s) = \frac{100s + 0.6614}{75s + 66.14} \tag{24}$$

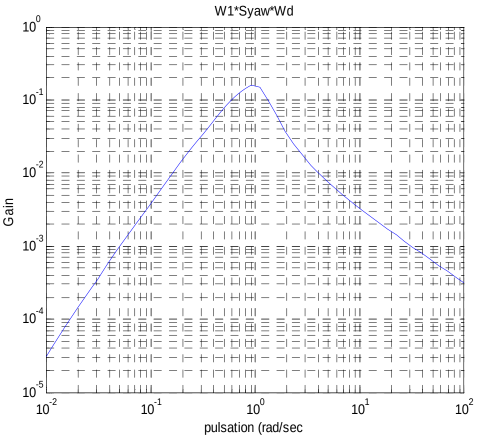

Figure 5. Gain plot of $\left(W_1 S_{yaw} W_d\right)$.

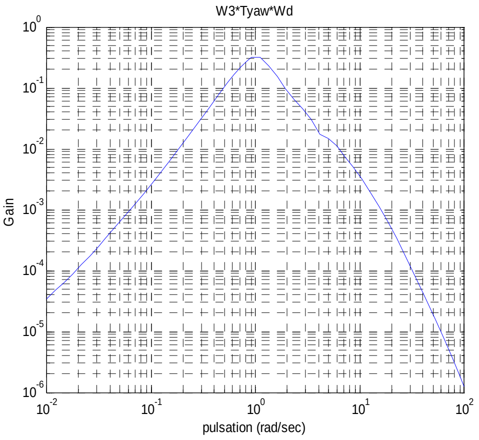

Figure 6. Gain plot of $\left(W_3 T_{yaw} W_d\right)$.

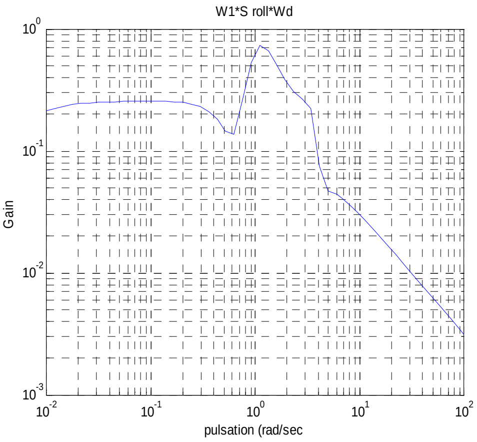

Figure 7. Gain plot of $\left(W_1 S_{roll} W_d\right)$.

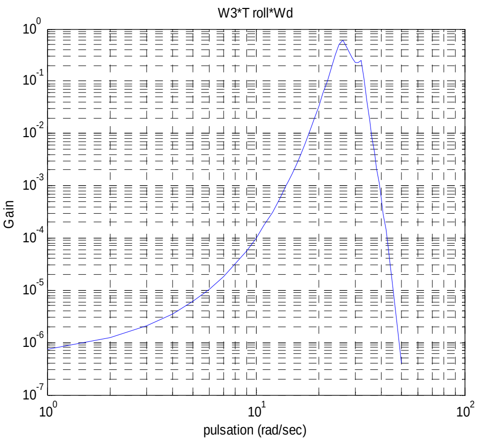

Figure 8. Gain plot of $\left(W_3 T_{roll} W_d\right)$.

4 SIMULATION RESULTS

The simulation concerns a container ship of L=230,66 *m* length, $m = 46{,}7\,10^{6}\,kg$ mass and $U_{nom} = 10{,}7\,m/s$ nominal speed. The other parameters necessary for modeling the ship can be found in [8]. The simulations concerns also two types of sea state conditions; a slight sea (sea state 3: $h_{1/3}$=0,875 *m* and T_w=4,680 *sec*) shown in Figure 9 and Figure 11 and moderate sea (sea state 4: $h_{1/3}$=1,875 *m* and T_w=6,850 *sec*) shown in Figure 10 and Figure 12.

In the case of slight sea, the roll angle disturbances can be ±21° (Figure 9). This disturbance on the roll angle is relatively important on the stability of the ship. In the second case (moderate sea), the roll angle disturbance (Figure 10) can reaches to ±50°. This case is more dangerous for the stability of the ship. So, it is necessary to reduce the effect of this disturbance.

Figure 11 and Figure 12 show yaw, roll and rudder angles in both sea state cases. One can see that the yaw static error is practically zero (±0,2° at maximum). The roll angle does not exceed ±0,3° that is absolutely acceptable. The angle of the rudder varies between ±13°, which is quite acceptable since the actuator is far from the saturation.

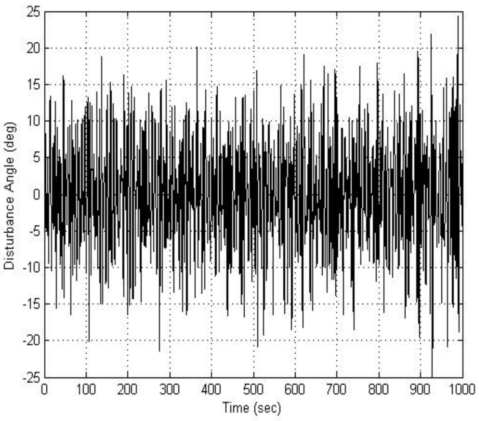

Figure 9. Disturbance angle for slight sea.

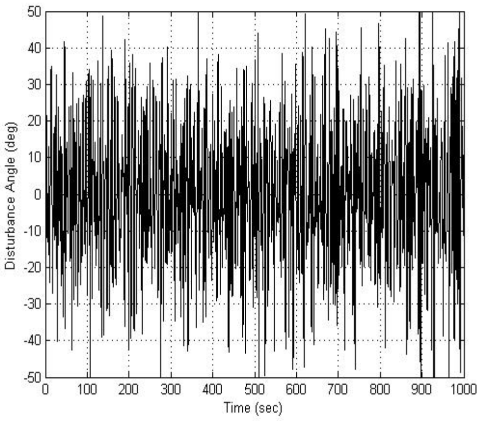

Figure10. Disturbance angle for moderate sea.

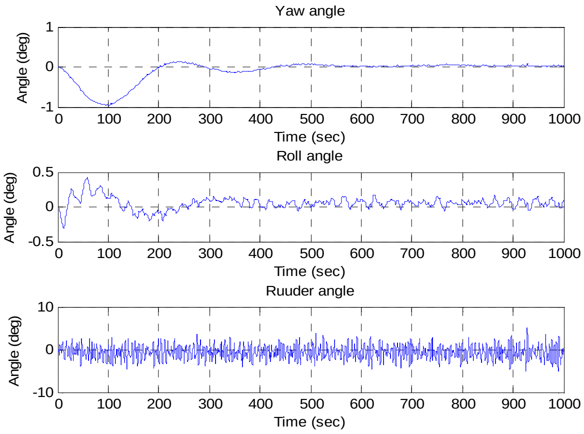

Figure 11. Yaw, Roll and Rudder angles for slight sea.

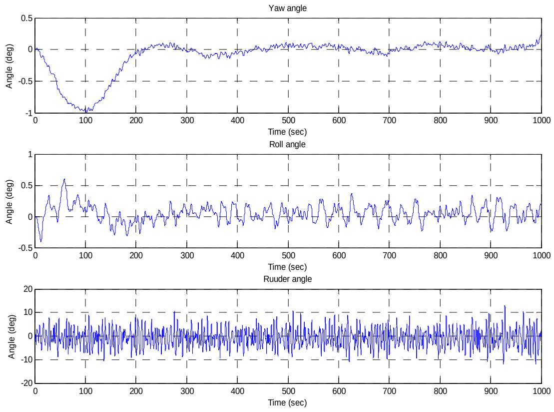

Figure 12. Yaw, Roll and Rudder angles for moderate sea.

5 CONCLUSION

This paper described the ship motion by the differential equations. The movements are generated by different phenomena: the propulsion of the ship, the effect of waves and the rudder motion. From the mechanical equations the state representation is obtained for the ship that is given in nonlinear, and then we deduce the linear model that it used for synthesizing an H_∞ control of the rudder which is in cascade structure.

By taking into account the wave model in the robust condition, robust control is designed that permits to reduce the roll motion of the ship and to maintain its heading in different conditions of navigation. The main difficulty is to determine weighting functions allowing this control signal stays in the unsaturated domain of the rudder. It can be achieved by a sensitive selection and after several tests.

Finally, it would be interesting to test other types of controller as sliding mode controller, fuzzy controller or multi-model controller while introducing several working points.

REFERENCES

[1] Perez, T., “Ship Motion Control”, Ed Springer, 2005.

[2] Amerongen, J. V., “Adaptive Steering of Ships – A Model Reference Approach to Improved Maneuvering and Economical Course Keeping”, PhD Thesis, Delft University of Technology, Netherlands, 1982.

[3] Yang, C., “A Robust Rudder Roll Damping Control”, PhD Thesis. Aalborg University, Denmark, 1998.

[4] Fossen T. I., “Guidance and Control of Ocean Vehicles”, John Wiley & Sons, N.Y. USA, 1994.

[5] Son, K. H. and K. Nomoto, "On The Coupled Motion of Steering and Rolling of A High Speed Container Ship", Journal of Naval Architecture and Ocean Engineering, Vol.20, pp.73-83, 1982.

[6] Kälström, C.G. and P. Otterson, "The generation and control of roll motion of ships in closed turns", Proc. of 4th-IFAC/IFIP Symposium on Ship Operation Automation, Genova, Italy, 1983.

[7] Blanke, M. and A. C. Christensen, "Rudder-Roll Damping Autopilot Robustness to Sway-Yaw-Roll Couplings", Proc. of The 10th International Ship Control Systems Symposium (SCSS'93), Vol. A, pp.93-119, Ottawa, Canada, 1993.

[8] Perez, T. and M. *Blanke,* "Mathematical Ship Modeling for Control Applications", Technical Report, Technical University of Denmark, 2002.

[9] SNAME, "Nomenclature for treating the motion of a submerged body through a fluid", Technical Report Bulletin 1-5, Society of Naval Architects and Marine Engineers, N. Y. USA, 1950.

[10] Saari, H., E. Khichane and M. Fedila, "Rudder Roll Reduction of Container Ship Using H_∞ Parallel Control Structure", Journal of Automation and System Engineering, Vol. 4(2), 2010.

[11] Morari, M. and E. Zafiriou, "Robust process control", Prentice Hall International, 1989.

[12] Khichane, E, "The Use of Modern Control Techniques for the Driving of Ships to Improve the Maritime Security : case of container ship", Master Thesis, Ecole Nationale Supérieure Maritime, Algeria, (2007).