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Design of container ship autopilot using robust Quantitative Feedback Theory

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***Abstract-** This paper describes the design of robust Quantitative Feedback Theory (QFT) autopilot for the course-changing control of a container ship. The ship model has parametric uncertainties, caused by the variations of hydrodynamic coefficients with the speed of the ship. Knowing the variation ranges of the model parameters, the QFT method can be used to design the ship autopilot with certain performance specifications. The autopilot must satisfy the robust stability and tracking performance, for all ship models generated by the parameter variations within the uncertainty region.*

Keywords: Ship autopilot, QFT Control, course-changing, ship model, bounds.

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-tracking maneuvers [1]. Applying more sophisticated autopilots for ship steering is mainly due to performance improvement and fuel economy [2].

The main purpose of the heading control systems (also called autopilot systems) is to control the steering machine, moving the rudder, so that the ship to track a desired route, which can be specified by way-points.

Ship steering control systems are designed to perform two entirely different functions: course keeping and course-changing maneuvers. In the first case, the autopilot acts to maintain the ship on a set course (between any two adjacent way-points). This type of system is fully autonomous; it does not need any operator to provide commands (orders) during operation. In the second case, the autopilot provides good maneuverability, changing the ship course to a new way-point, in accordance with commanded course changes given by the superior control level or pilot/helmsman. In general, the yaw angle changes are small enough so the linear ship models can be used. However, for large maneuvers, the nonlinear ship models must be taken into account.

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For this purpose we choose to design a controller using the Quantitative Feedback Theory (QFT) which is a frequency domain robust-design methodology for control systems where the plant is uncertain. The idea has been applied to scalar, multivariable, linear, nonlinear and invariant time varying uncertain systems. The technique has attracted considerable interest in theory and engineering applications, such as aeronautics, aerospace industry, robotics, electronics and electrical engineering.

In addition, the operational conditions (e.g. trim, load or ballast condition, speed changes, water depth) affect the ship dynamics, modifying the hydrodynamic coefficients of the ship and the corresponding parameters of ship model. If the mathematical model of the controlled physical process presents parametric uncertainties, it is necessary to use robust control techniques for controller design. Since the model parameters of the ship's yaw motion depend on the forward speed as well as the weather conditions, the ship model presents parametric uncertainties.

Various robust control design technique, like H_∞ control [3], sliding mode control [4], fuzzy control [5], multi controller [6], … etc have been applied to handle this problem. But most of the cases, using the designed controllers depend on the course condition of the ship. Marine systems require a controller which is independent of the identification of course condition. Further, ideally a single controller should be capable to handle all variations in marine plant parameters for entire performance envelope of operation. Therefore, the QFT method has been chosen for the autopilot design [7, 8, 9 and10].

The course-keeping autopilot takes into account the wave influence on the yaw motion, corrected with the ship's speed and the incidence angle. Robust stability and input disturbance rejection conditions are specified, to meet the course-keeping requirements in the presence of the wave disturbances [8]. The course-changing autopilot satisfies some performance specifications, like robust stability and tracking performance conditions. The goal of this paper is to design a robust QFT autopilot for course-changing applied to a container ship.

This paper is organized as follows. Section 2 gives an overview of the QFT. In section 3, the mathematical model of the ship used in simulations is presented. Section 4 is devoted to the presentation of stability and tracking specifications. Section 5 describes the design steps for robust QFT autopilot and simulations results to the application of the autopilot to container ship model are presented. Finally, some conclusions are presented in section 6.

2. ABOUT THE QFT

QFT is a unified frequency domain technique utilizing the Nichols chart (NC) for achieving the desired robust design over a specified region of plant uncertainty. This method was created and developed by Professor Horwitz (1963) which is now recognized as a well established method for design of robust controllers for plants with large classes of uncertainties, output /input disturbances and noises. This method has been implemented successfully in process control, flight control, marine control, missile control, power systems and power electronics applications, robot manipulator control, to name a few. The true importance of feedback is in 'achieving desired performance despite uncertainty'. Hence, the actual design and the cost of feedback should be closely related to the extent of the uncertainty and to the narrowness of the performance tolerances [7]. The QFT design is based upon:

- Specifying the tolerances in frequency domain (time domain tolerances should be converted into corresponding frequency domain tolerances) by means of set of plant transfer functions and closed-loop control ratios, and

- Tune the loop transmission functions and pre-filter functions to satisfy various results corresponding to the tolerances.

A single-loop feedback control structure is shown in Fig. 1, where, *P* is the set of transfer functions {*P(s)*}, which describe the region of plant parameter uncertainty, *G(s)* is the cascade compensator, and *F(s)* is an input pre-filter. The output *Y(s)* is required to track the command input *R(s)* and to reject the external disturbance *D(s).* The compensator *G(s)* is to be designed in such a manner that the variation of *Y(s)* to the uncertainty in the plant *P* is within allowable tolerances, the robustness criteria is ensured and the disturbance rejection requirement is met. In addition, the pre-filter properties of *F(s)* must be designed to reach the responses to meet the tracking specification requirements.

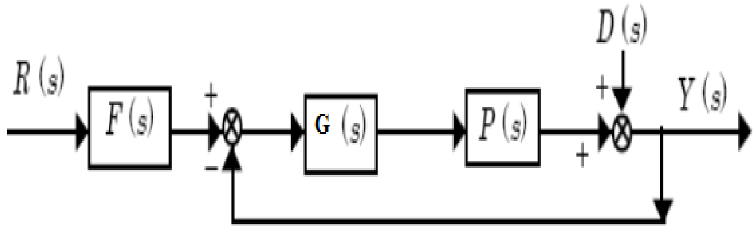

Figure1. QFT control system.

3. MATHEMATICAL MODEL OF THE PROCESS

Conventional ship autopilot for course-keeping and course-changing control problems involves the heading angle feedback as illustrated in Fig. 2. The yaw motion of the ship is described by the transfer function *P(s)* from the rudder angle (δ) to the course angle (ψ). The autopilot generates the rudder commands, based on the course error (ψ_e). The autopilot has two linear components: the compensator *G(s)* and the pre-filter *F(s)*.

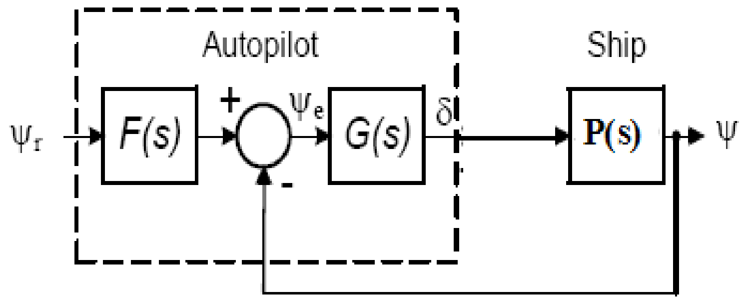

Figure2. QFT autopilot structure.

The equations describing the horizontal motion of a ship are derived by using Newton's laws, expressing conservation of hydrodynamic forces and moments. Then, the model can be simplified applying Taylor series for hydrodynamic forces and moments [11]. A three degree-of-freedom linear model is obtained for asymmetric ship motions, with coupled sway-yaw-roll equations, which can be identified.

The monovariable linear model of the ship's dynamics for yaw motion, without considering any perturbations, can be represented as a first order Nomoto model [12], whose differential equation is:

$$\ddot{\psi}(t)+\frac{1}{T}\cdot\dot{\psi}(t)=\frac{K}{T}\cdot\delta(t) \qquad (1)$$

The corresponding transfer function is:

$$P(s)=\frac{K}{s\cdot(T\cdot s+1)} \qquad (2)$$

where the parameters K and T depend on the operating conditions such as ship's speed, load or ballast situation, water depth etc. The Nomoto model provides a reasonably accurate representation, if the rudder angles are relatively small. This is the case for course-keeping control and for slight course-changes. Also, the model can be used for course-changing problem, if the way-points of the desired route are computed and generated so that smooth rudder angles are obtained.

4. FEEDBACK DESIGN WITH QFT

4.1. Uncertain region of the ship model

The hydrodynamic characteristics of the ship depend on the speed [1]. This dependency was identified, for different ship's speed: 12.3, 19.7, 24.7, 29.7 and 32 knots which correspond respectively to: 6.3, 10, 12.7, 15.2 and 16.5 m/s. Parameters K and T of (2) can take one of these values:

K= {-0.0129, -0.0254, -0.0376, -0.0553, -0.0676}

T= {6.6299, 12.1056, 15.8865, 20.7414, 23.9309}

An uncertainty region appears, generated by the value ranges of ship parameters. This region is illustrated in Fig. 3. If the performance specifications are met for the plant models placed on the contour of uncertainty region, then they are met for all plant models into the region. Therefore, only a small number (N) of models on the contour must be selected for QFT design, 16 different ship models appear on the contour (N=16).

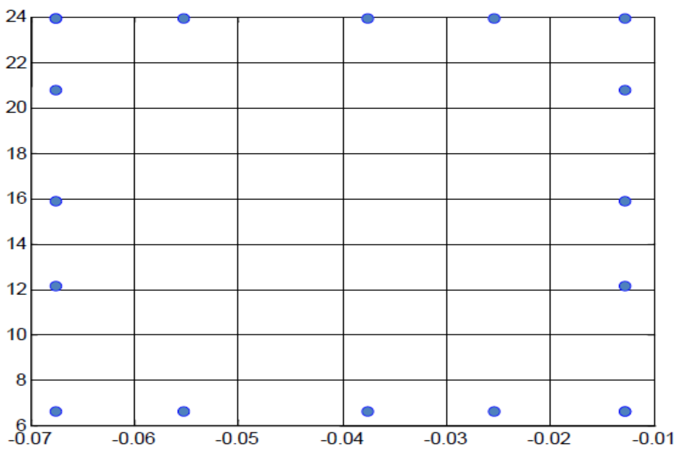

Figure 3. Plant uncertain region.

4.2. Ship model templates

The goal of this step is to obtain ship model templates at specified frequencies that pictorially describe the region of plant parameter uncertainty on the Nichols chart [10]. Then, the nominal ship model is chosen. For every point of a chosen frequency vector into the system bandwidth, a ship model template is obtained in Nichols chart, by computing the frequency responses of all ship models (N = 16) selected on the contour of the uncertainty region. The template shape depends on the frequency value. Starting from low frequencies, the template width increases, then as frequency takes on larger values, the templates become narrower, tending to a vertical line when the frequency tends to infinity. In Fig. 4, six templates are represented, corresponding to six frequency values into the system bandwidth:

Ω = {0.02, 0.05, 0.1, 0.2, 0.5 and 1} rad/s

In order to perform QFT design with a single nominal loop, choosing the nominal plant is required. As long as the set satisfies the assumptions on the uncertainty model given in Continuous-Time; one may choose any plant case. One chooses the one, which we think is most convenient for design;

The chosen nominal ship model is:

$$P_0(s) = \frac{-0.0376}{s \cdot (15.8865 \cdot s + 1)} \tag{3}$$

which corresponds to the nominal speed of the ship of 12.7m/s

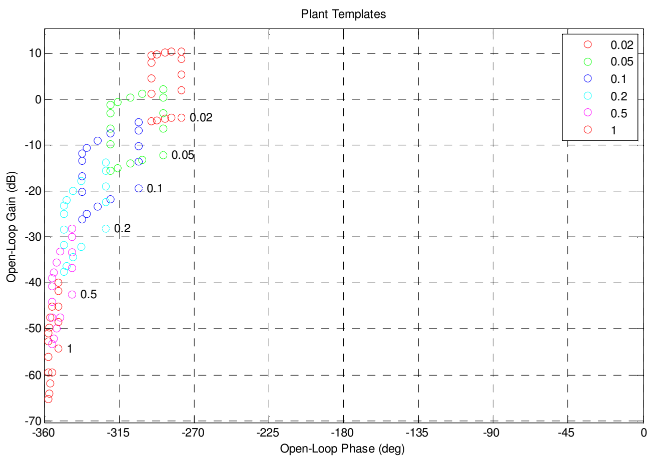

Figure 4. Ship model templates for six frequency values.

4.3. Robust Stability Specifications

The robust stability indicates that a closed-loop system is stable for any plant within the specified uncertainty model. To achieve the robust stability, two conditions should be verified:

- Stability of nominal system
- The generated templates and the loop transmission function *L(jω)* don't penetrate the region generated by the NC.

The closed loop transfer function is:

$$H_B(s) = \frac{G(s) \cdot P(s)}{1 + G(s) \cdot P(s)} = \frac{L(s)}{1 + L(s)} \tag{4}$$

where *L(s)* represents the loop transmission function.

For all the chosen frequencies, the envelope of the magnitude characteristics must be smaller than a maximum value α_B:

$$\max_{P(s),\omega}\left(\left|H_B(j\omega)\right|\right) \le \alpha_B \tag{5}$$

where in general α_B < 2dB. The chosen value is α_B = 1.2dB. The stability specifications must be met.

4.4. Robust Tracking Specifications

The course changes must be defined within acceptable range of variations. When a course change is ordered, the reference course followed by the vessel can be specified by means of a second order reference model [8]:

$$H_0(s) = \frac{\omega_0^2}{s^2 + 2\zeta\omega_0 s + \omega_0^2} \tag{6}$$

where ω_0 is the natural frequency and ξ is the damping coefficient of the closed loop reference model.

For course-changing without oscillations, the damping coefficient is recommended to be between 0.8 and 1 [1]. In this paper, the selected values are: ω_0= 0.5 rad/s and ξ= 0.85.

The closed loop tracking system has the transfer function:

$$H_T(s) = \frac{F(s)\cdot G(s)\cdot P(s)}{1+G(s)\cdot P(s)} = \frac{F(s)\cdot L(s)}{1+L(s)} \tag{7}$$

All ship models have parameters variation which causes the variation of the closed loop system, but it should remain within specific limits. These limits are defined by two transfer functions, denoted respectively lower bound ($H_{0L}(s)$) and upper bound ($H_{0U}(s)$) which satisfy:

$$\left|H_{0L}(j\omega)\right| \le \left|H_T(j\omega)\right| \le \left|H_{0U}(j\omega)\right| \tag{8}$$

The two transfer functions represent robust tracking tolerances and must include the reference model H_0:

$$\left|H_{0L}(j\omega)\right| \le \left|H_0(j\omega)\right| \le \left|H_{0U}(j\omega)\right| \tag{9}$$

Hence, the lower and upper limit transfer functions are selected around the second order reference model:

$$H_{0L}(s) = \frac{a_1 a_2 a_3}{(s+a_1)(s+a_2)(s+a_3)} \tag{10}$$

$$H_{0U}(s) = \frac{\frac{\omega_0^2}{a}(s+a)}{s^2 + 2\zeta\omega_0 s + \omega_0^2} \tag{11}$$

where the parameter values are: a_1=0.5ω_0, a_2=1.5ω_0, a_3=2ω_0 *and* a=1.2ω_0

The magnitude characteristics of the desired second order reference model, lower and upper limit transfer functions are illustrated in Fig. 5. The continuous line corresponds to the reference model and the dashed lines illustrate the tracking tolerances of the lower and upper bounds. It can be observed that the ship dynamics of the yaw motion are important for very low frequencies and they decrease rapidly for frequencies bigger than ω_0=0.5 rad/s. Fig. 6 represents the step response of the desired reference model, lower and upper transfer functions.

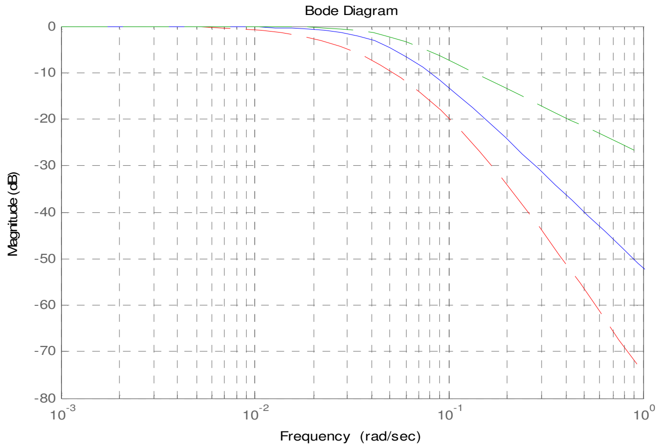

Figure 5. Magnitude characteristics of the reference and tracking bound models.

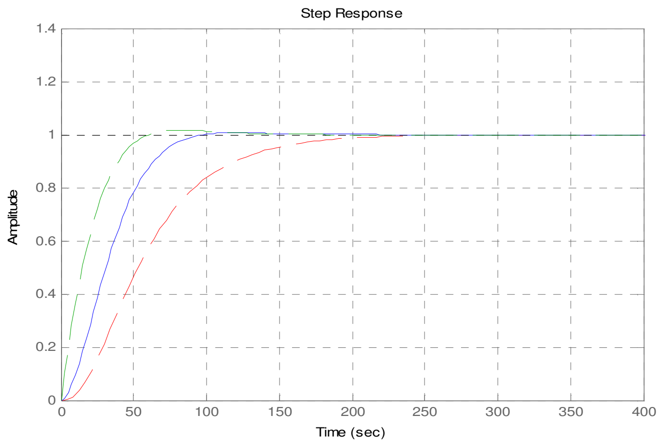

Figure 6. Step responses of the reference and tracking bound models.

5. DESIGN AND SIMULATIONS RESULTS

In this paper, we will design a course-changing autopilot, so the robust stability and tracking specifications should be satisfied.

Due to the pre-filter $F(s)$, the autopilot acts like a real-PD controller on reference channel, which is sufficient if the course change commands are step type signals.

The bounds of robust stability and robust tracking are calculated, on the basis of the performance specifications, using *sisobnds.m* function from QFT Matlab Toolbox [10]. These bounds are illustrated in Fig. 7 and Fig. 8. The closed contours represent the stability bounds for all six frequency values of set **Ω.** For every frequency value, the optimal bounds are calculated by intersecting all the bounds, as illustrated in Fig. 9, using *sectbnds.m* function from QFT Matlab Toolbox [10].

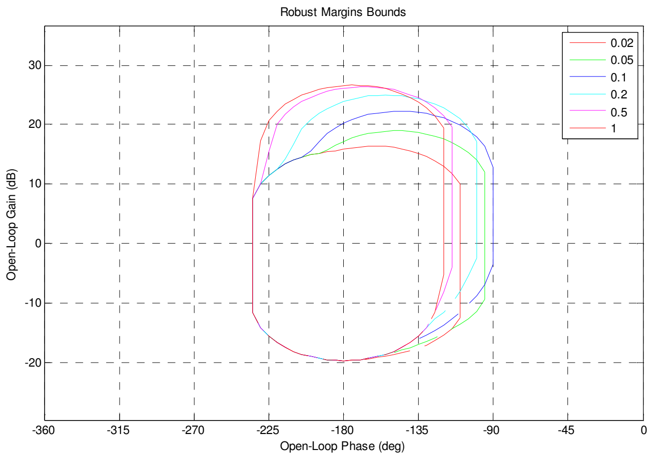

Figure 7. Robust stability bounds.

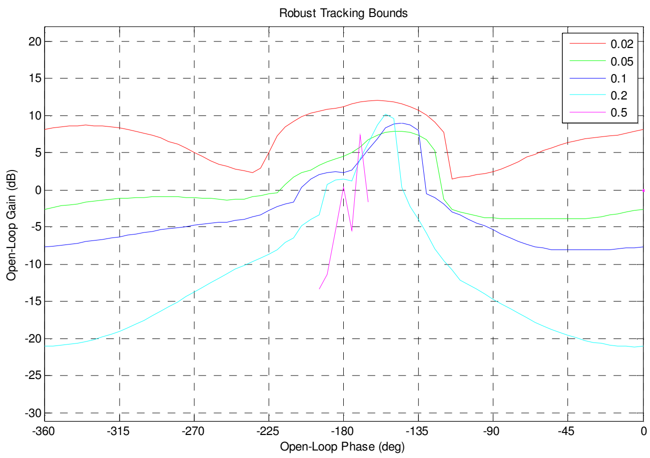

Figure 8. Robust tracking bounds

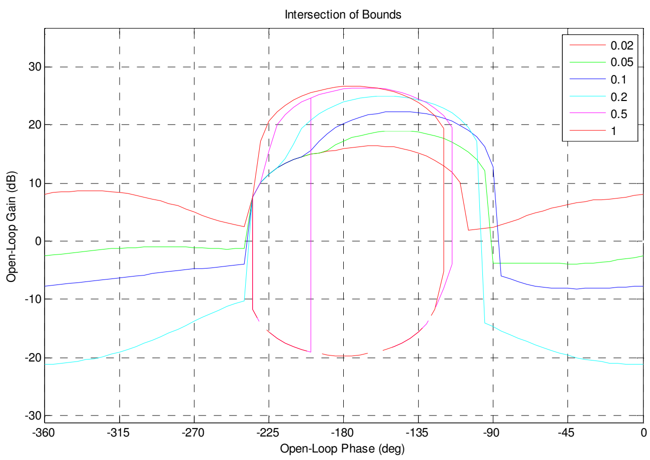

Figure 9. Bound intersection.

The design objective is to design the compensator $G(s)$ and the pre-filter $F(s)$ so the specified robust design is achieved for the given region of plant parameter uncertainty. The design procedure to accomplish this objective is as follows:

5.1. Controller tuning

On the same Nichols chart, the transfer function of the nominal loop transmission is represented (vertical line) by:

$$L_0(s) = G(s) \cdot P_0(s) \tag{12}$$

where the initial expression of compensator *G(s)* can be chosen. We start the loop shaping with $G(s) = 1$, represented in Fig. 10.

The nominal loop transmission is calculated for an extended frequency vector. For this, the *lpshape.m* QFT Matlab function is used, which is a controller design environment for continuous-time linear systems. It produces the Nichols plot for the nominal loop transmission, while the compensator expression can be modified into an interactive manner. In this way, modifying the compensator expression, the nominal loop transmission is synthesized to satisfy the optimal bounds, without penetrating the closed contours. For every frequency value, the values of nominal loop transmission must be on or above the corresponding values of optimal bounds.

The expression of the compensator is given by (13). The corresponding Nichols plot of the nominal loop transmission is illustrated in Fig. 11. This controller satisfies all specifications and all bounds for every frequency.

$$G(s) = (-16.8)\frac{\left(\frac{1}{0.07}s + 1\right)}{\left(\frac{1}{4}s + 1\right)} \tag{13}$$

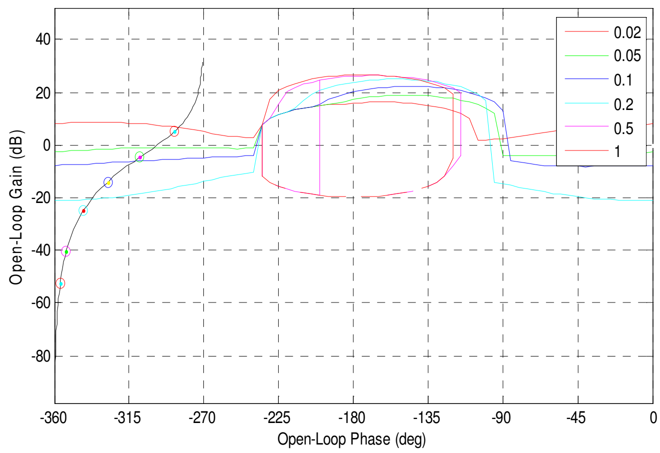

Figure 10. Controller loop shaping *G(s)*=1.

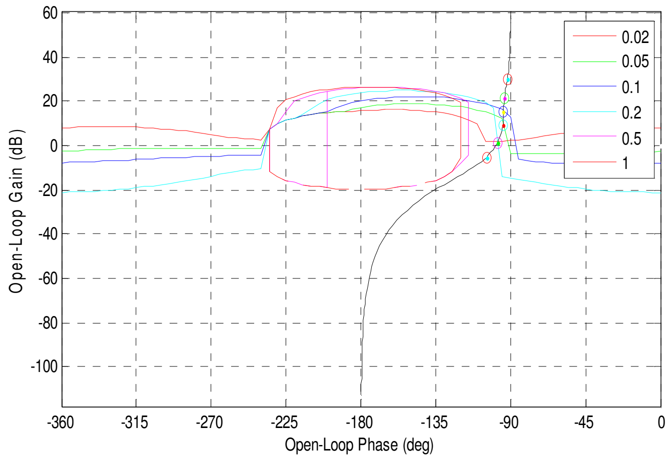

Figure 11. Final loop shaping after adjusting the gain.

5.2. Pre-filter design

The pre-filter *F(s)* is synthesized to satisfy the tracking specifications, by modifying the expression interactively, starting from an initial value of 1. The parameters of pre-filter are modified, until the tracking specifications are met.

Using the pre-filter (14), the tracking specifications are satisfied, as shown in Fig. 12. In this case, the upper and lower envelopes of the closed loop system with pre-filter are inside of the tracking limits (illustrated with dashed lines).

$$F(s) = \frac{1}{(33.33s + 1)} \tag{14}$$

The closed loop system verifies the robust stability specification, as shown in Fig. 13. The maximum value $\alpha_B = 1.2\,dB$ is represented with dashed line. The maximum magnitude characteristic envelope is smaller than the specified value for the entire working bandwidth.

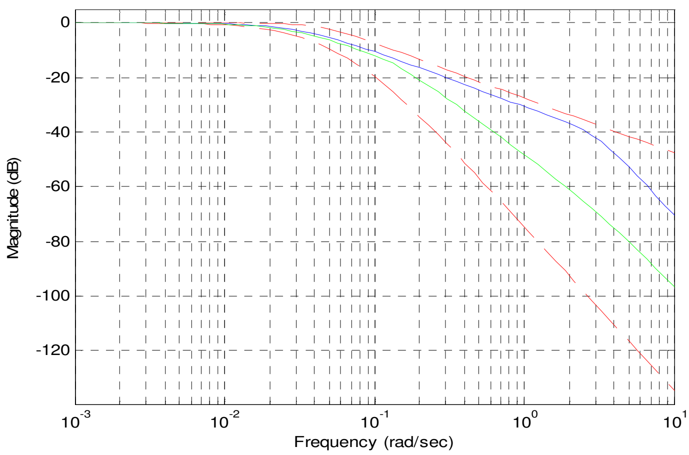

Figure 12. Upper and lower magnitude envelopes of closed loop system.

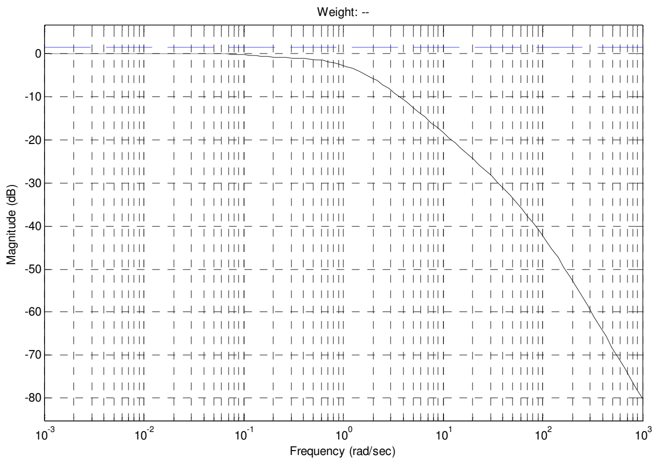

Figure 13. Robust stability verification for course changing autopilot.

5.2. Simulation results

The step responses of the closed loop system for all the ship models considered on the contour of the uncertainty region (N=16) are illustrated in Fig. 14. The course followed by the ship remains into the specified limits and approximates the second order reference model. As we can see from the Fig. 14, the step response satisfies the tracking conditions.

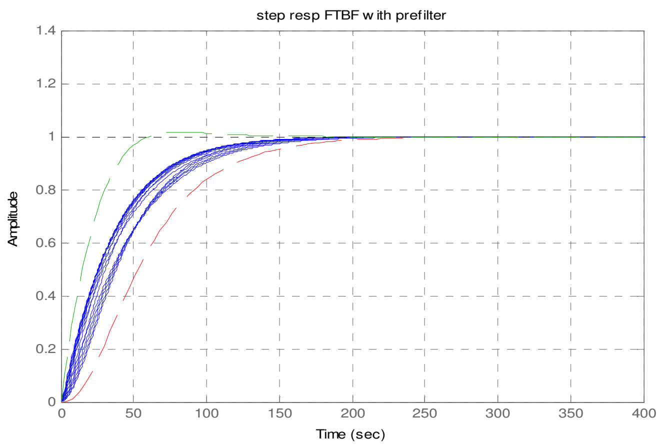

Figure 14. Step response of closed loop system.

6. CONCLUSION

Robust QFT ship autopilot is designed, for the course-changing control of a ship. The ship model has parametric uncertainties due to the forward speed, which affects hydrodynamic coefficients. Knowing the variation ranges of the model parameters, QFT autopilot can be design to satisfy performance specifications. The autopilot satisfies the robust stability, tracking performance, for all ship models generated by the uncertainty region.

In this paper we have used the QFT Robust control to synthesize a course tracking autopilot for a container ship. This tuning was applied to a Nomoto linear model which gives a very good and satisfactory result.

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