ROBUST QFT CONTROLLER FOR MARINE COURSE-CHANGING CONTROL

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Abstract: This paper describes the design of a robust QFT (Quantitative Feedback Theory) controller for the control of the changing of a ship's course in the presence of disturbances. A linear model is used with uncertainties in the parameters obtained from the non-linear model of the ship. The required performance specifications and the existing number of plants determine the bounds which the system must not violate. The results are compared with those obtained with a conventional PID controller by means of genetic algorithms.

Keywords: ship control, ship autopilots, marine systems, control systems, ship model, course-changing control, plant templates, bounds, QFT control.

1. INTRODUCTION

In any physical process which one aims to control, certain performance specifications must be fulfilled. If the mathematical model of the system is not exact or if there are external disturbances, that is, if the system presents uncertainties, it is then necessary to use robust control techniques in the design of the controller. Among the different techniques available, the QFT (Quantitative Feedback Theory) method developed by Horowitz (1992) has been chosen for this work. With this model, the physical dimension of the problem is maintained at all times and an adequate balance is achieved between the structure level of the process and the complexity of the problem.

The above method is applied in this work for the course-changing control of the ship, the R.O.V. Zeefakkel (Fossen and Paulsen, 1992), using for the design of the QFT controller the first order Nomoto model (Nomoto, et al., 1957) which relates the heading angle with the rudder angle. Saturation effects have been taken into account in the design. The results are compared with those of a conventional autopilot.

2. MATHEMATICAL MODEL OF THE VESSEL

Figure 1 shows the block diagram of a ship steering system with a conventional autopilot (PID controller). Saturation effects have been taken into account both in the rudder angle and in the speed of change of this angle.

The command applied is ψ_r, which represents the desired heading and ψ_e is the heading error. The control signal of the controller which acts as a command to the steering gear is δ_c and represents the rudder angle required to correct the deviation from the heading. The actual value of the rudder angle is δ and ψ is the ship's course.

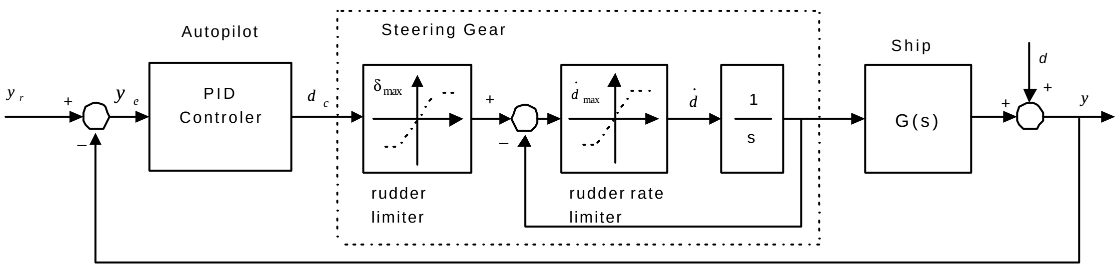

Fig. 1. Block diagram of a conventional steering system

The mathematical model of the ship's dynamics between the rudder angle signal δ and that of the ship's course y assuming that the relation is linear (Van Amerongen and Udink Ten Cate, 1975), can be represented (Nomoto, et al., 1957) by the transfer function:

$$\frac{y}{d}(s) = \frac{K(1+sT_3)}{s(1+sT_1)(1+sT_2)} \qquad (1)$$

or equally by the differential equation:

$$T_1T_2\dddot{\o} + (T_1+T_2)\ddot{\o} + \dot{\o} = K(\ddot{a} + T_3\dot{\ddot{a}}) \quad (2)$$

where K, T_1, T_2 and T_3 are the parameters which represent the ship's dynamics. These parameters are basically determined by the dimensions and forms of the vessel and also depend on operating conditions such as ship speed, load or ballast situation, draft, trim and water depth.

Equation (1) is usually approximated by

$$\frac{y}{d}(s) = \frac{K}{s(1+sT)} \qquad (3)$$

with $T = T_1 + T_2 - T_3$.

Expressed as a differential equation:

$$T\ddot{\o} + \dot{\o} = K\ddot{a} \quad (4)$$

This attractively simple model provides a reasonably accurate representation of the performance of vessels when they keep a straight course or one with only slight changes. However, if the characteristics of the vessel's rotation are to be studied, a non-linear term (Van Amerongen and Udink Ten Cate, 1975) can be added to the linear model:

$$T_1T_2\dddot{\o} + (T_1+T_2)\ddot{\o} + KH_B(\dot{\o}) = K(\ddot{a} + T_3\dot{\ddot{a}}) \quad (5)$$

where $H_B(\dot{\psi})$ is a non-linear function of $\dot{y}$ which is obtained from the relation between $\dot{y}$ and δ in the steady state by means of the spiral test. This can be approximated (Van Amerongen and Udink Ten Cate, 1975) by:

$$H_B(\dot{y}) = b_3\dot{y}^3 + b_1\dot{y} \qquad (6)$$

If equation (4) is used, we get

$$T\ddot{\o} + H_N(\dot{\o}) = K\ddot{a} \qquad (7)$$

with

$$H_N(\dot{y}) = n_3\dot{y}^3 + n_1\dot{y} \qquad (8)$$

3. CONTROL PROBLEM

An autopilot must fulfil two objectives: course keeping and course changing. In the first case, the control objective is to maintain the ship's heading following the desired course ($y(t)$ = constant). In the second case, the aim is to implement the change of course without oscillations and in the shortest time possible. In both situations, the operability of the system must be independent of the disturbances produced by the wind, the waves and the currents.

The course followed by a vessel can be specified by means of a second order reference model (Fossen, 1994):

$$\ddot{\psi}(t) + 2\zeta\omega_n\dot{\psi}(t) + \omega_n^2\psi(t) = \omega_n^2\psi_r \quad (9)$$

where ω_n is the natural frequency and ζ ($0,8 \le \zeta \le 1$) is the desired damping coefficient of the closed loop system.

As an application of the proposed methodology, the simulation of the behaviour of a vessel of 45m in length, the R. O. V. Zeefakkel, is performed. The model's parameters at a speed of 10 knots are (Fossen and Paulsen, 1992):

$$K = 0.5\ s^{-1},\ T = 31\ s,\ n_1 = 1,\ n_3 = 0.4\ s^2$$

4. DESIGN SPECIFICATIONS

The aim of the design of this work is that the vessel should make a fast change of course following, without oscillations, the course determined by the values ζ = 0.9 and ω_n = 0.07 rad/s and that this course should be maintained despite the effect of bow waves in the order of 1m in significant height. (Moyano, et al., 2000) It is considered that these may lead to variations in the course of up to 1°.

The non-linearities in the ship model mean that the performance in response to changes in course may vary. The prior study of this effect has led the authors to consider for the model design the vessel given by equation (3) with the following uncertainty in the K and T parameters (at a speed of 10 knots):

$K \in [0.21, 0.5]$
$T \in [29.5, 31]$

Despite the fact that the model is non-linear, the QFT model for linear SISO systems with parametric uncertainty will be used, incorporating the two-degrees-of-freedom control system shown in figure 2. This includes a cascade compensator, G(s), and a prefilter F(s) (both LTI) in order to reduce the variations in the output of the system caused by the uncertainties in the plant parameters and disturbances.

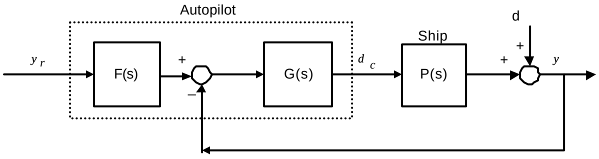

Fig. 2 Block diagram of the two degree-of-freedom control system

The system must fulfil robust stability and robust tracking specifications (Houpis and Rasmussen, 1999; Yaniv, 1999):

For the robust stability margins, the phase margin angle should be at least 45º and the gain margin 2 dB. Thus, the robust stability specification is defined by:

$$\left|\frac{P(j\omega)\,G(j\omega)}{1+P(j\omega)\,G(j\omega)}\right| \le \delta = 1.2 \qquad (10)$$

Robust tracking: The change of course must be defined within an acceptable range of variation. This is generally defined in the time domain but is normally transformed to the frequency domain, being expressed by:

$$T_{RL}(jw) \le T_R(jw) \le T_{RU}(jw) \qquad (11)$$

where $T_R(s)$ represents the closed loop transfer function and $T_{RL}(s)$ and $T_{RU}(s)$ the equivalent transfer functions of the lower and upper tracking bounds. In this case, the following is specified:

$$T_{RL}(s) = \frac{a}{s^3 + b\ s^2 + c\ s + a} \qquad (12)$$

with a =269.5*10^{-6}, b = 181*10^{-3}, c = 118.3*10^{-4}

$$T_{RU}(s) = \frac{195 * 10^{-4} s + 49 * 10^{-4}}{s^2 + 112 * 10^{-3} s + 49 * 10^{-4}} \qquad (13)$$

for $\omega \le 0.4$ rad/s, as shown in Figure 3.

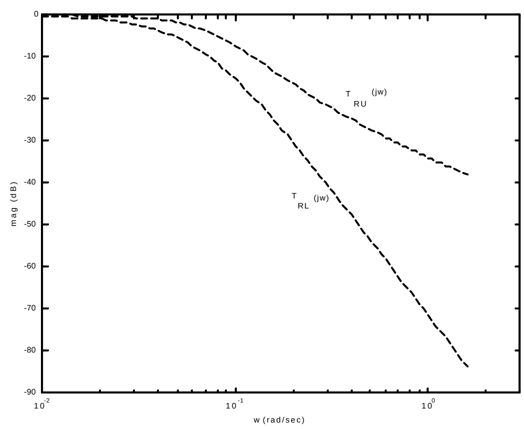

Fig. 3 Robust tracking specifications.

As mentioned above, the aim of the design is to maintain the course even when there are bow waves. No disturbance rejection restriction has been specified because the simulation considers only waves of a reasonable force.

5. SIMULATIONS

The following nominal plant has been chosen for the design:

$$P(s) = \frac{0.5}{s(31s+1)} \qquad (14)$$

and the following set of frequencies for the design has been established:

$$\Omega = \{0.03,\ 0.07,\ 0.1,\ 0.2,\ 0.4,\ 1,\ 1.2\} \qquad (15)$$

Using the Matlab QFT Toolbox (Borguesani, et al., 1995) the plant templates are computed for each frequency, as shown in Figure 4.

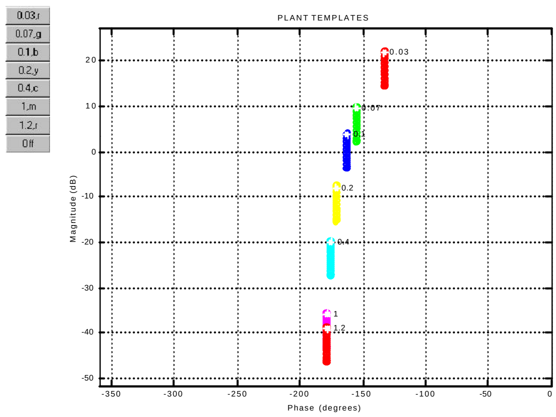

Fig. 4 Plant Templates.

On the basis of the performance specifications and the plant templates, the robust stability and robust tracking bounds are calculated. The intersection of all of the bounds at the various frequencies is shown in Figure 5.

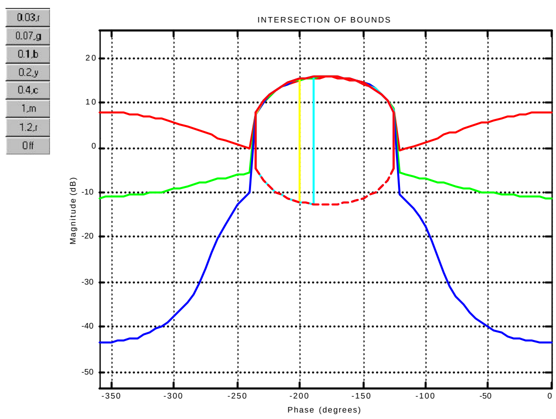

Fig. 5 Intersection of bounds.

For the design of the G(s) controller, the Nichols Chart is used, adjusting the nominal open-loop transfer function $L_0 = P_0G$ (P_0 is the nominal plant) in such a way that no bounds are violated, as shown in Figure 6.

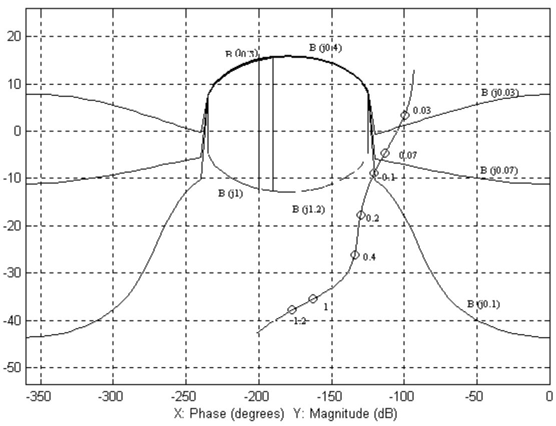

Fig. 6 Shaping of $L_0(j\omega)$ on the Nichols chart for the nominal plant.

The controller obtained is:

$$G(s)=\frac{180.45*10^{-3}s^3+625.38*10^{-3}s^2+16.57*10^{-3}s+36.92*10^{-7}}{s^4+168.53*10^{-2}s^3+203.23*10^{-2}s^2+18.73*10^{-2}s} \qquad (16)$$

With this controller, the robust stability specification is fulfilled but not the robust tracking specification, as can be seen from Figures 7 and 8. The solid line shows the response of the system and the dashed line represents the specifications.

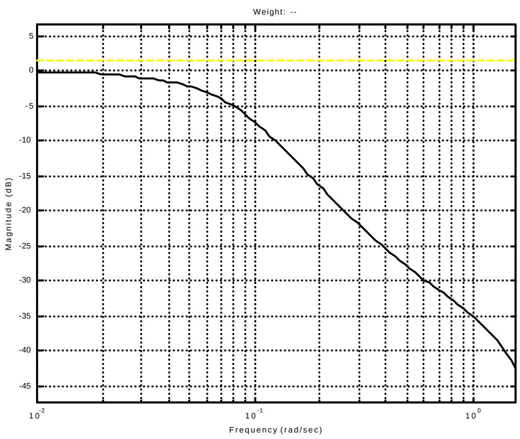

Fig. 7 Robust Stability

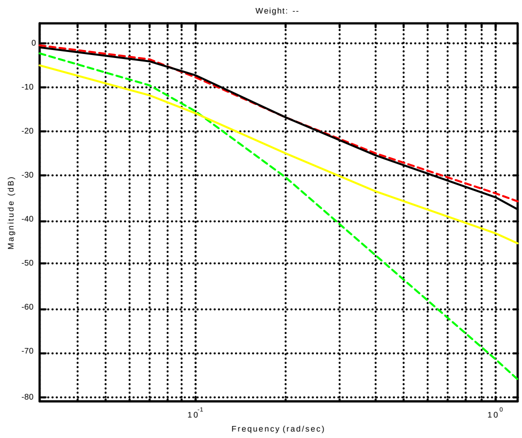

Fig. 8 Robust Tracking

By adjusting the prefilter:

$$F(s)=\frac{128.89*10^{-3}}{s+128.89*10^{-3}} \qquad (17)$$

a restriction on the frequency response of the system is obtained such that it is maintained within the limits imposed in the design. It is also verified that the control structure designed allows the ship's course to fit the specifications for various course changes. As examples, Figures 9 and 10 show the results for changes in course of 10º and 30º respectively.

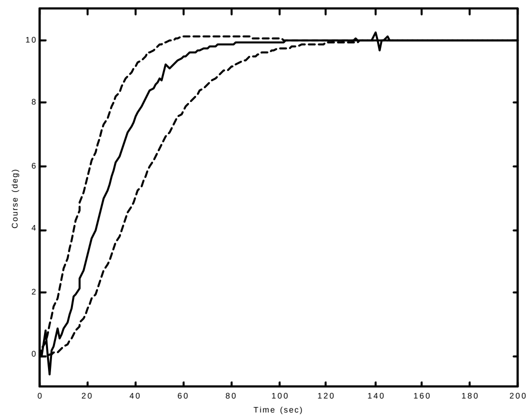

Fig. 9 Course changing manoeuvre. $\psi_r = 10^o$

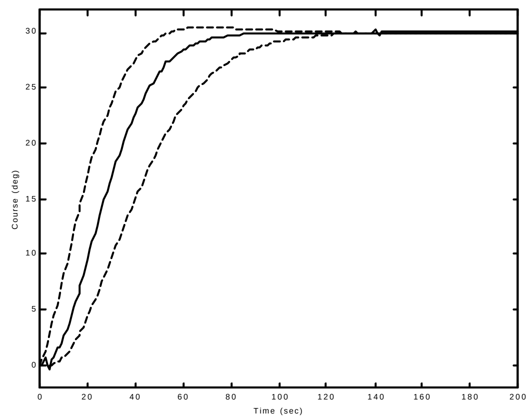

Fig. 10 Course changing manoeuvre. $\psi_r = 30^o$

The change of course manoeuvre obtained with QFT design has been compared with that of a vessel with a conventional PID controller which has been tuned by means of genetic algorithms:

$$G(s) = \frac{15523.7s^2 + 448.37s + 0.1}{44737s^2 + 4473.7s} \qquad (18)$$

Figure 11 shows a change of course manoeuvre of 10º for the two controllers and Figure 12 illustrates the required variations in the rudder angle (control signal).

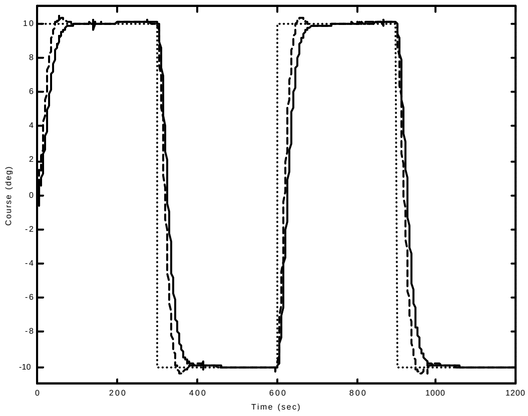

Fig. 11. Change of course manoeuvres for the QFT (solid line) and PID (dashed line) controllers. Reference heading (dotted line).

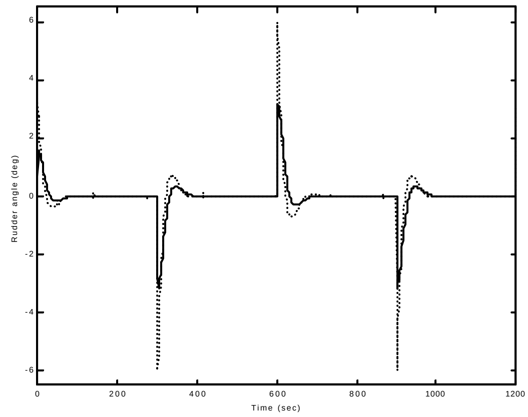

Fig. 12. Rudder Angle. QFT signal control (solid line), PID signal control (dotted line)

6. CONCLUSIONS

This paper describes the use of the QFT robust control technique which is highly suitable since the system presents uncertainties and disturbances. Robust stability and robust tracking specifications have been imposed. The results have been compared with those obtained using a conventional PID controller. It can be observed that a more satisfactory result is obtained with the QFT controller in the response of the system at the expense of an increase in the complexity of the control.

7. ACKNOWLEDGEMENTS

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