Journal of Maritime Research, Vol. II. No. 1, pp. 69-86, 2005
Copyright © 2005. SEECMAR

Printed in Santander (Spain). All rights reserved
ISSN: 1697-4840

APPLICATION OF A ROBUST QFT LINEAR CONTROL METHOD TO THE COURSE CHANGING MANOEUVRING OF A SHIP

T. M. Rueda[1], F. J. Velasco[1], E. Moyano[2], E. López[3], J.M. de la Cruz[4]

ABSTRACT

This paper describes in detail the design methodology of a robust QFT (Quantitative Feedback Theory) controller for the control of the course changing of a ship. A linear model is used with uncertainty in the parameters. The system is designed to fulfil the specifications of robust stability and robust tracking of a reference system.

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

INTRODUCTION

If a control system were represented by a fixed, known mathematical model and, if this model were available even in the presence of disturbances, the design of the controller required to attain the desired behaviur specifications would be a relatively simple matter. However, the mathematical model of the system can present variations due, amongst other things, to modeling errors or to the effects of external disturbances. In order to reduce the sensitivity of the system to these uncertainties, a closed loop control system is required. The designed controller must also be robust in order to attain the required specifications, even when faced with uncertainty in the model and the presence of disturbances. The quantity of feedback required will be directly proportionate to the degree of uncertainty and to the desired reduction in sensitivity.

[1] Dept. Electronics Technology and Systems Engineering and Automatics. Univ. de Cantabria (ruedat@unican.es) (velascof@unican.es)
[2] Dept. of Applied Mathematics and Computation Sciences. Univ. de Cantabria. (moyanoe@unican.es)
[3] Dept. of Sciences & Techniques of Navig., Marine Engines and Ship Cons. UPV. (cnplogae@lg.ehu.es)
[4] Dept. of Computer Science and Systems Engineering. Univ. Complutense (jmcruz@dacya.ucm.es)

In the 1960s, Isaac Horowitz (1963) introduced an efficient robust control design technique in the frequency domain, known as the "Quantitative Feedback Theory" or QFT. This technique considers a priori the uncertainty that may be present in the process and its environment and establishes a balance between the quantity of feedback required and the design complexity. The controller designed with this method is of minimum cost, does not have a large gain and minimises the control effort. Moreover, it has a smaller bandwidth than that obtained using any other design technique dealing with special structures and their uncertainties, disturbances and/or specifications.

The QFT method has already been applied in the design of different types of control systems for, for example, flight control (Houpis et al., 1994), control of an activated sludge wastewater treatment plant (Ostolaza and García Sanz, 1997), robot control systems (Yaniv and Horowitz, 1990; Kelemen and Bagchi, 1993; Piedmonte et al., 1998; Choi et al., 1999), stabilisation of the vertical movement of a ship (Aranda et al., 2002; Velasco et al., 2004).

This paper presents the application of this method to the control of the course changing manoeuvring for a ship (Rueda and Velasco, 2000 and Rueda, T.M. 2005). Course control is of special interest for joint operations between ships such as assistance to a damaged ship, towing manoeuvres and going along side or two ships sailing close to each other. A Matlab QFT toolbox (Borguesani, 1995) is used for the design and analysis of the control system.

METHODOLOGY. QFT DESIGN TECHNIQUE FOR LINEAR SYSTEMS

The QFT design technique is characterised mainly by its consideration a priori of the uncertainty of the process, caused by the variations in the parameters of the equipment to be controlled and by external disturbances and takes into account in the controller design process both the gain and its phase. It attempts to minimise the control effort in order to avoid saturations in the actuators or in the plant, which can be caused by the amplification of the sensor noise required to reach the desired specifications with a minimum bandwidth. With this method, a robust controller is obtained which is insensitive to the uncertainties of the process. The system model may be given as a transfer function or using experimental data. The representation in state variables is not normally used, since it is rather more complex. This technique makes it possible to predict quite simply whether some desired behaviour specification will not be fulfilled and to rectify the design accordingly without using complex mathematical tools. With this design method, a controller can be selected in graph form in the frequency domain.

The QFT method proposes as a general control strategy the two degrees of freedom structure presented in Figure 1, in which both compensators (F(s) and G(s)) are LTI, linear and time invariant.

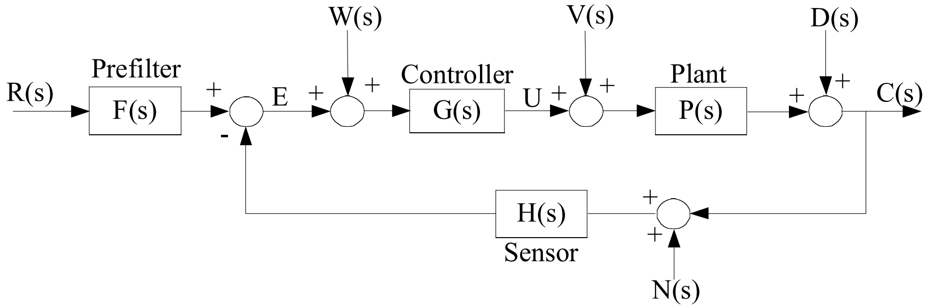


Figure 1: Two degrees of freedom control structure

Below, we will applied the QFT technique to the design of the control system for the course changing manoeuvre for a Mariner class cargo ship (Rueda and Velasco, 2000).

DEVELOPMENT

Mathematical Model for Course Control of a Ship

In the literature (Fossen, 1994), linear and non-linear techniques are proposed which describe the basic dynamics for the course control on the horizontal plane. Figure 2 shows the block diagram of a ship's steering system.

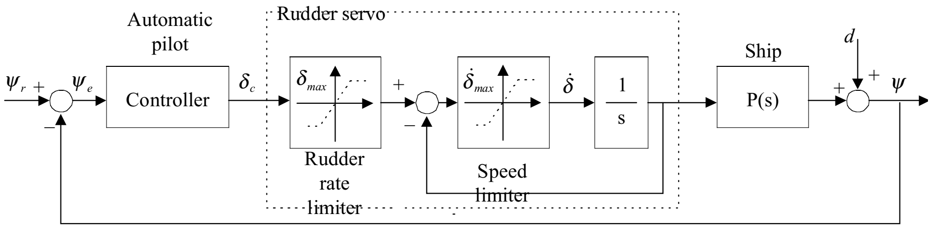


Figure 2: Ship's steering system

The command applied is ψ_r, which represents the desired course, ψ_e is the error in the course; the control signal which acts as the command on the rudder servomotor is δ_c, and represents the rudder angle required to correct the course deviation. The actual value of the ru dder angle is δ, and ψ is the ship's course. The effects of saturation are considered both in the rudder angle and in the speed of change of this angle.

Control Problem

The objectives to be performed by an automatic pilot are:

Course-keeping: Maintain the heading of a ship following a given course ($\psi(t)$ = constant).

Course changing: This manoeuvre must be performed in the minimum time possible, without overshoots at the beginning and end of the operation, to show clearly to the other ships the intentions of the manoeuvre. This can be achieved by using a second order reference model to determine the trajectory (Fossen, 1994):

$$\ddot{\psi}(t)+2\zeta\omega_n\dot{\psi}(t)+\omega_n^2\psi(t)=\omega_n^2\psi_r \tag{1}$$

where ζ ($0,8 \leq \zeta \leq 1$) is the desired closed loop damping ratio, and ω_n is the natural frequency, whose value depends on the the ship's dynamics.

In both situations, the system must work efficiently, independently of the disturbances caused by the wind, waves and currents.

APPLICATION: COURSE CONTROL FOR A SHIP WITH A LINEAR MATHEMATICAL MODEL

Definition of Design Problem

Nomoto et al. (1957) propose, for the analysis of ship stability and the design of automatic pilots, an approximate first order model:

$$\frac{\psi}{\delta}(s)=\frac{K}{s(1+sT)} \tag{2}$$

where T is the value of an effective time constant $(T=T_1+T_2-T_3)$

The parameters K, T_1, T_2 y T_3 represent the ship's dynamics. These are determined by the dimensions and forms of the ship, depending also on operating conditions, such as speed, load, ballast, draft, trim and depth of water.

One ship represented by the above mathematical model is the Mariner class cargo ship, (Fossen, 1994) with:

$$K = \text{-}0.185 \text{ s}^{-1} \qquad \left.\begin{array}{l} T_1 = 118 \text{ s} \\ T_2 = 7.8 \text{ s} \\ T_3 = 18.5 \text{ s} \end{array}\right| T = 107.3 \text{ s} \tag{3}$$

The ship model to carry out the design of a QFT controller, assuming that the K and T parameters show uncertainty, is:

$$P(s)=\frac{\psi}{\delta}(s)=\frac{K}{s(1+sT)} \text{ with } \left|\begin{array}{l} K \in [\text{-}0.135,\ \text{-}0.235] \\ T \in [80.3,\ 134.3] \end{array}\right. \tag{4}$$

The system should fulfil the following specifications:

1. Robust stability:Phase margin of at least 45º, gain margin of 2 dB

2. Robust tracking of reference signal, desired course: the course changing manoeuvre must be defined within an acceptable range of variation with respect to a reference signal. The lower bound will be a course change which is slower than the reference. The upper bound will be a master course-change than the reference. Figure 3 shows the specified bounds.

These bounds correspond to the trajectory defined by the response to the step input of the following A(s) and B(s) functions:

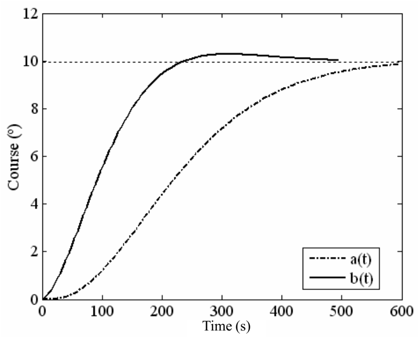


Figure 3: Bounds in the time domain

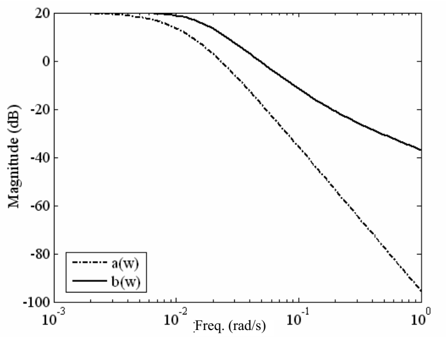


Figura 4: Bounds in the frequency domain

$$A(s)=\frac{168*10^{-8}}{s^3+0.03424s^2+40.3366*10^{-5}s+168*10^{-8}}$$

$$B(s)=\frac{14.0625*10^{-4}s+225*10^{-6}}{s^2+0.0225s+225*10^{-6}} \qquad (5)$$

To apply the QFT design technique, the specifications need to be defined in the frequency domain. Thus, for the case under study:

$$a(\omega)\le T(j\omega)\le b(\omega) \qquad (6)$$

where T is the closed loop reference transfer function.

Figure 4 shows the representation in frequency domain of the established tolerances.

In order to fulfil both specifications, a QFT controller will be designed made up of the compensator G(s) and the pre-filter F(s) of the two degrees of freedom system of Fig. 5.

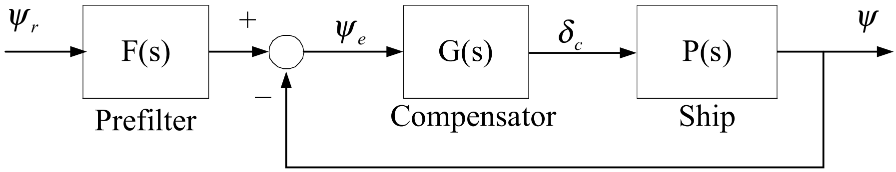


Figure 5: QFT control of course changing

Selection of Design Parameters

The second step in the design process is to select a nominal plant $P_0(s)$ from among the family of plants ***P(s)***. An adequate and finite set of frequencies **Ω** must also be selected. This set is determined by the bandwidth of the system and by the frequencies of interest, for which the different desired behaviour specifications are defined. In this case, the nominal plant selected is:

$$P_0(s) = \frac{-0.135}{s(107.3s+1)} \tag{7}$$

Taking into account the frequency response bounds permitted, Figure 5, it choose as a set of design frequencies:

$$\Omega = \{0.003,\ 0.007,\ 0.01,\ 0.02,\ 0.05,\ 0.1\}\text{rad/s} \tag{8}$$

Design

The third step in the design process is to represent as accurately as posible the uncertainty of the system. When the system is not defined by a single model, but rather has several due to the parametric uncertainty, the frequency response of the system for a given frequency is represented by a set of points, as many as there are different models. All of these points define a region of uncertainty known as template. There will be as many templates as frequencies in the set **Ω**.

The most common way to calculate a template is to perform a sweep of the values that the model parameters can take. In this study case, a sweep is made of the values that can be taken by the parameters K and T. The extremes of the uncertainty intervals are taken as references, and these values have been selected:

K = {-0.135, -0.16, -0.185, -0.235}

T = {80.3, 95.3, 107.3, 122.3, 134.3}

In order to perform the control system design, it suffices to consider the contour of a template, since if this contour respects the regions forbidden by the specifications, the rest of the templates will do too (García-Sanz and Vital, 1999).

The templates obtained for the family of plants ***P(s)*** and for the set of frequencies Ω are as shown in Figure 6.

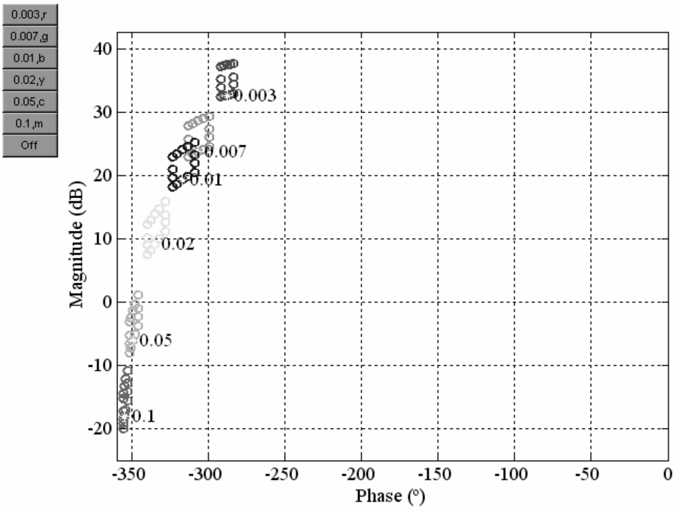


Figure 6: Templates

Each point represents the frequency response of one plant of the family and each colour distinguishes the response for each value of the frequency range. The shape of the templates varies with the frequency and its size decreases when the frequency increases.

Obtaining the Bounds

The fourth step in the design is to define, in QFT terminology, the desired behaviour restrictions. The specifications given, combined with the uncertainty of the system, form what are termed bounds. They are represented on the magnitude$_{dB}$-phase plane, and there is one for each frequency and specification; they are denoted as $B(w)$.

These curves are the objects which define the bounds of the regions prohibited for the adjustment of the controller. If the transfer function of the controller is denoted as $G(jw)$ and the transfer function of the nominal plant as $P_0(jw)$, the bounds are those regions that the open loop function frequency response $L_0(jw)$ ($L_0(jw) = G(jw)P_0(jw)$) must avoid in order to guarantee the fulfilment of the design specifications for the whole set of plants ***P(jw)***. In order to use the QFT method, the bounds need to be defined in the frequency range.

The procedure for obtaining in graph form the bound for each frequency and each specification is immediately available through the Matlab QFT toolbox.

Robust Stability

Relative stability is normally expressed in terms of certain desired gain margins and phases. These are related with a value in decibels δ, known as the M-circle because it takes this shape if represented in a magnitude$_{dB}$-phase diagram. This circle identifies an exclusion zone around the point [-180º, 0dB], which the loop function must not cross ($\forall\omega\in\Omega, \forall P\in \boldsymbol{P}$) in order to ensure the margin of minimum stability. The specification of robust stability is written as:

$$\left|\frac{P(j\omega)G(j\omega)H(j\omega)}{1+P(j\omega)G(j\omega)H(j\omega)}\right| \le W_{S_1} = \delta \tag{9}$$

relating it with the gain margin (GM) and phase (PM) as follows:

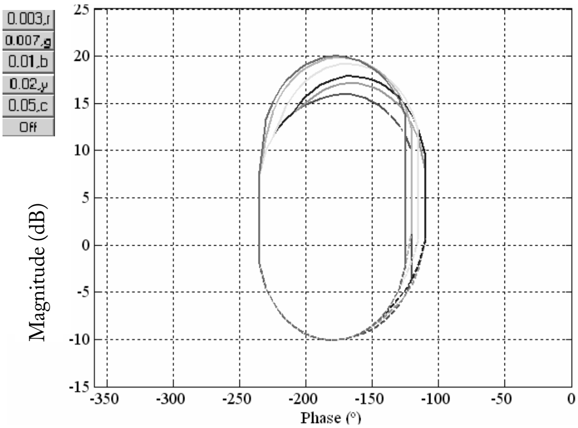
$$\begin{aligned} GM &= 1+\frac{1}{\delta} \\ PM &= 180-\cos^{-1}\left(\frac{0.5}{\delta^2}-1\right) \end{aligned} \tag{10}$$

For the example proposed, a phase margin of at least 45º and a gain margin of 2 dB were specified.

Thus, the following should be fulfilled:

$$\left|\frac{P_0(j\grave{u})G(j\grave{u})}{1+P_0(j\grave{u})G(j\grave{u})}\right| \le \delta = 1.2 \tag{11}$$

Taking into account the specifications imposed and the uncertainty of the model, the bounds for robust stability are as shown in Figure 7.



The bounds for the frequency range Ω are represented by the following colour code: ω = 0.003 rad/s in red, 0.007 rad/s in green, 0.01 rad/s in blue, 0.02 rad/s in yellow, 0.05 rad/s in light blue and 0.1 rad/s in magenta. This will apply to all of the bounds graphs.

Figure 7:
Robust stability bounds

When the bounds are represented by a continuous line and are closed, the specification is verified if the frequency response of the loop function for each frequency is outside the curve corresponding to the same frequency.

Robust tracking of a reference signal

The tracking specification is established by means of lower, a(t), and upper, b(t), bounds in the system response. It is considered that both functions have Laplace transform A(s) and B(s). For the example used, it was specified that the response to a course changing should be kept within the bounds given in Figure 5. In order to apply the QFT technique, this specification is defined in the frequency domain as follows

$$a(\omega) \leq 20\log\left|T(j\omega)\right| \leq b(\omega), \quad \forall \omega \in \Omega, \forall P(s) \in \boldsymbol{P}(s) \qquad (12)$$

where *T(jw)* is the closed loop transfer function of the system.
For the QFT design, the specification is established as follows:

$$W_{S_{7a}} \leq \left|\frac{P(j\omega)G(j\omega)}{1+P(j\omega)G(j\omega)H(j\omega)}\right| \leq W_{S_{7b}} \qquad (13)$$

where:

$$\begin{aligned} W_{S_{7a}} &= \left|a(\omega)\right| \\ W_{S_{7b}} &= \left|b(\omega)\right| \end{aligned} \qquad (14)$$

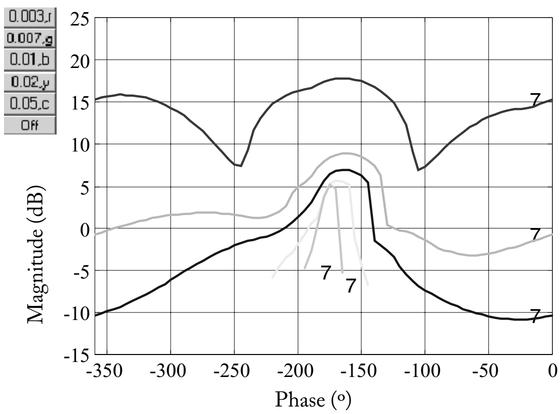


Figure 8: Robust tracking bounds

In the example, in order to obtain robust tracking bounds, a subset of Ω is considered, and it is required that the specification is verified only for frequencies lower than 0.05 rad/s. Combining the specification and the uncertainty, the robust tracking bounds of Figure 8 are obtained.

The robust tracking bounds are open and have a continuous line. Thus, the open loop response, *L(jw)* , for each frequency must be adjusted so that this point is located above the bound corresponding to this same frequency. Thus, it is ensured that the specification is fulflled.

Tuning of the Controller

The fifth step in the design of the control system consists in finding a controller with which all of the desired specifications are fulfilled. It is also known as the synthesis or "loop-shaping" phase.

The method consists in assuming an initial value of the controller function $G_0(jw)$, and adjusting the loop function $L_0(jw)$ which verifies the imposed restrictions and minimises the control effort. The adjustment is made using the Matlab QFT Toolbox, shifting the loop curve vertically and horizontally on the magnitude$_{dB}$-phase plane, until it is situated in such a way as to not violate the bounds and as to have the lowest gain possible.

For the example of the Mariner class cargo ship, and assuming an initial controller of a constant value, $G_0(s)=1$.

The representation of the loop function is a curve with several points marked in colours. These points correspond to the response of the loop for the various frequencies defined in Ω, following the same colour code as in the bounds. The loop adjustment must be done in such a way that each coloured point is close to the bound of the same colour, and same frequency. It must also be taken into account whether the bound is a continuous line or not. If they are all continuous, the point must be above for open curves (ω = 0.003, 0.007, 0.01 rad/s) and outside for closed curves (ω = 0.02, 0.05, 0.1 rad/s).

This part of the design process is not automated in the Matlab toolbox; obtaining a good design with little overdesign depends greatly on the skill of the designer. There is no single or perfect solution.

The controller is related with the loop function as follows:

$$L_0(j\omega) = G(j\omega)P_0(j\omega) \tag{15}$$

In this way, once the loop is adjusted, it is simple to obtain the transfer function of the compensator. The controller obtained is robust, that is, it provides good results for all of the family of plants defined by the uncertainty, not only for the nominal plant used in the loop-shaping stage.

It is recommended, in this loop-shaping stage, to always begin by adjusting the point corresponding to the lowest frequency, continuing upwards and modifying the function progressively.

For the example of the course changing manoeuvre, the terms included are:

1.- Reduce the system gain to adjust the frequency w = 0.003 rad/s. The loop function point for this same frequency, in red, must be above the bound at this frequency, also in red, and as near as possible, so that there is as little as possible overdesign. For the compensator $G_1(s)$, this condition is fulfilled, as can be seen in Figure 9.

$$G_1(s) = -0.0692 * G_0(s)$$
$$L_1(j\omega) = G_1(j\omega) P_0(j\omega) \qquad (16)$$

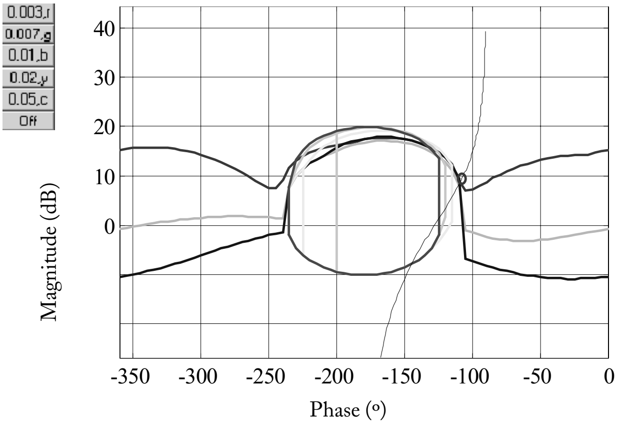


Figure 9: Loop function L1 and bounds

2- Add phase-lead, a real zero. This achieves the adjustment of the conditions for the frequencies 0.007 rad/s, green, and 0.01 rad/s, blue. The position of the loop at these frequencies must follow the same criteria as that of step 1. Figure 10 shows that the conditions are verified for the following $G_2(s)$ controller:

$$G_2(s) = G_1(s) * \left(\frac{s}{0.01585} + 1 \right)$$
$$L_2(j\omega) = G_2(j\omega) P_0(j\omega) \qquad (17)$$

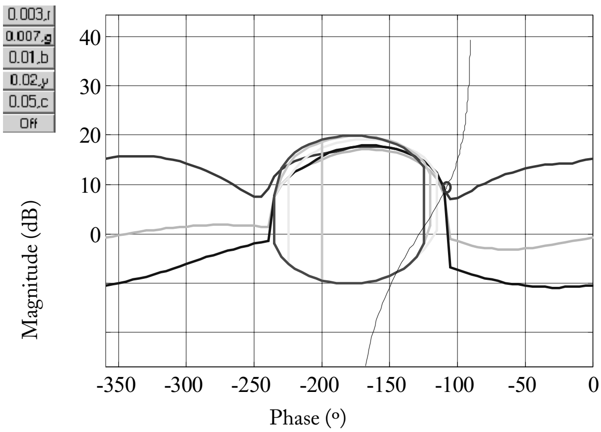


Figure 10: Loop function L2 and bounds

3º- There are also bounds for the frequencies of 0.02 rad/s, yellow, 0.05 rad/s, light blue, and 0.1 rad/s, magenta. In these cases, the point corresponding to the loop must be outside the oval. This is fulfilled, so that it will not be necessary to modify the obtained compensator. However, the closer the corresponding bound points, the lower the feedback cost. A certain improvement is observed in Figure 11; this is achieved by adding two complex poles conjugated with the natural frequency ω_n = 0.1783 rad/s and damping ratio δ = 0.1099, obtaining the controller $G_3(s)$.

$$G_3(s) = G_2(s) * \frac{1}{\left(\frac{s^2}{0.1783^2} + \frac{2*0.1099}{0.1783}s + 1\right)}$$
$$L_3(j\omega) = G_3(j\omega)P_0(j\omega) \tag{18}$$

The compensator $G(s)$ obtained finally is:

$$G(s) = \frac{-0.1388s - 0.0022}{s^2 + 0.0392s + 0.0318} \tag{19}$$

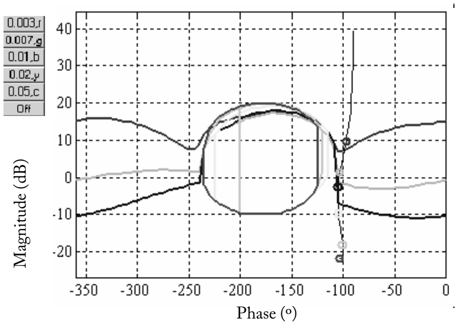


Figure 11: Loop function L3 and bounds

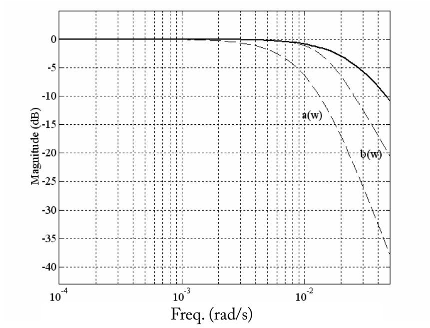


Figure 12: Robust tracking

The design of the controller with which the robust tracking bounds are respected in the loop function frequency response is performed in two stages. The uncertainty of the system means that there is a maximum and a minimum response. The first step in the design is to tune the compensator $G(s)$, so as to reduce the difference between the two responses. The second step consists in adjusting a pre-filter $F(s)$, which transfers the variations obtained with the above design to the zone defined by the tolerances $b(w)$ and $a(w)$. That is, the definition of equation 6 can be written as:

$$a(\omega) \le |F(j\omega)|_{dB} + |T_l(j\omega)|_{dB} \le b(\omega)$$
$$T_l(j\omega) = \frac{L(j\omega)}{1 + L(j\omega)} \tag{20}$$
$$T(j\omega) = F(j\omega)T_l(j\omega)$$

Figure 12 shows the frequency response of the system with the controller Q but, without the prefilter F, it is not within the bounds

The adjustment of the prefilter is performed graphically by shifting the system response curve using the mouse, so that it is within the required tolerances. In this case, we get:

$$F(s) = \frac{1}{104.51s + 1} \tag{21}$$

Design Validation

As the last step in the design process, a validation of the obtained results should be made, graphically checking the specifications in the frequency and time domains.

Moreover, this validation is essential, since the design has been made only for a finite set of frequencies and hence it cannot be ensured, a priori, that it will be fulfilled for any other frequency, inside or outside this range. Thus, it needs to be checked for a higher number of frequencies.

For the proposed example, it is verified whether the specifications are fulfilled for a new range of frequencies Ω_v, for 100 values logarithmically spaced between 10^{-4} and 0.1 rad/s.

Figure 13 shows with a dotted line the desired stability value (δ = 1.2 = 1.58 dB) and with a continuous line the system response. As this latter value is below the specification line, the required robust stability condition is fulfilled.

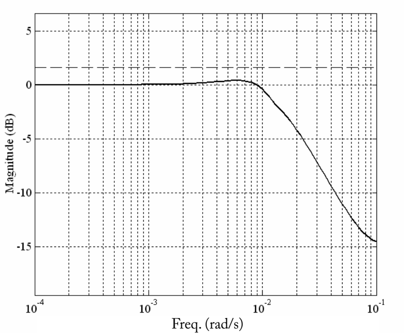


Figure 13: Robust Stability

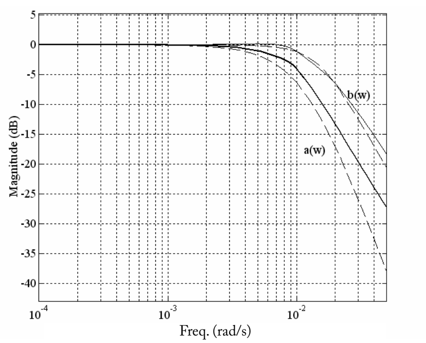


Figure 14: Robust tracking with compensator and prefilter

Figure 14 shows that the conditions of robust tracking are fulfilled for the course changing manoeuvre in the frequency domain; the system response, in a continuous line, is within the permitted tolerance, in the dotted line.

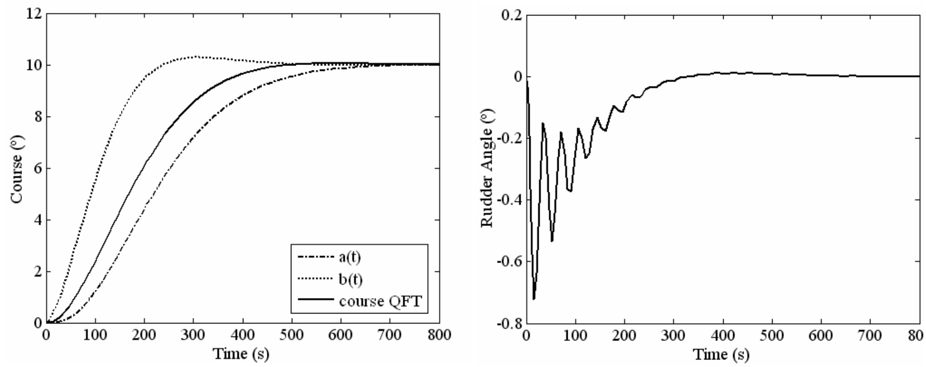


Figure 15.a: Course changing manoeuvre

Figure 15.b: Rudder angle

Course changing manoeuvre in the time domain

The course changing manoeuvre must be within the permitted tolerantes a(t) and b(t). Figure 15.a shows that this is fulfilled. Figure 15.b shows the rudder angle required to carry out this manoeuvre.

CONCLUSIONS

A linear QFT robust control methodology has been applied to the course changing manoeuvre for a ship. It has been demonstrated that this technique is suitable for application in this case, which presents uncertainties in the parameters.

It has been verified, by means of simulation, that the required specifications of robust stability and robust tracking are fulfilled.

Another important factor is the small control effort required to perform this course changing manoeuvre.

ACKNOWLEDGEMENTS

This work has been partially financed by the MCYT through project DPI2003-09745-C04-03.

REFERENCES

Aranda, J., De la Cruz, J. M., Díaz, J. M. and Dormido Canto, S. (2002) QFT Versus Classical Gain Scheduling: Study for a Fast Ferry. *Control 15th IFAC World Conference*.

Borguesani, C., Chait, Y. and Yaniv, O. 1995. *Quantitative Feedback Theory Toolbox – For use with MATLAB*. The MathWorks Inc.

Choi, S. B., Cho, S. S. and Park, Y. P. (1999) Vibration and Position Tracking Control of Piezoceramic-based Smart Structures via QFT. *ASME Journal of Dynamic Systems, Measurement and Control* (121), 27-33.

Fossen, T. I. (1994). Guidance and Control of Ocean Vehicles. John Wiley and Sons Ltd., England.

García-Sanz, M. and Vital, P. (1999) Efficient Computation of the Frequency Representation of Uncertain Systems. *Proceedings 4th International Symposium on QFT and Robust Frequency Domain Methods*. Durban, South Africa.

Horowitz, I. M. (1963) *Synthesis of Feedback Systems*. Academic Press. New York.

Houpis, C. H., Sating, R. R., Rasmussen, S. and Sheldon, S. (1994) Quantitative Feedback Theory Technique and Applications. *International Journal of Control* 59, 3970.

Kelemen, M. and Bagchi, A. (1993) Modelling and Feedback Control of a Flexible Arm of a Robot for Prescribed Frequency Domain Tolerances. *Automatica* (29), 899-909.

Nomoto, K., Taguchi, T., Honda, K. and Hirano S. (1957). On the steering qualities of Ships. International Shipbuilding. Progrees (4).

Ostolaza, J. X. and García-Sanz, M. (1997) Control of an Activated Sludge Wastewater Treatment Plant with Nitrification-Denitrification Configuration using QFT Technique. *Proceedings of Symposium on Quantitative Feedback Theory and Other Frequency Domain Methods and Applications*, University of Strathclyde, Glasgow, Scotland.

Piedmonte, M. D., Mechl, P. H., Nwokah, O. D. and Francheck, M. A. (1998) Multivariable Vibration Control of a Coupled Flexible Structure using QFT. *International Journal of Control* (69) 475-498.

Rueda, T. M. and Velasco, F. J. (2000) Robust Course-Changing Controller for a Ship using QFT Design Technique. 2nd International Congress on Maritime Technological Innovations and Research. Cádiz.

Rueda, T.M. (2005). *Metodología de reducción de modelos y control robusto QFT para el gobierno y estabilización de buques*. Tesis doctoral. Departamento de Tecnología Electrónica e Ingeniería de Sistemas y Automática. Santander.

Velasco, F. J., Rueda, T. M. López, E. and Moyano, E. (2004) Pitch Movement QFT Control to Reduce the MSI of a Turbo Ferry. *IFAC Conference CAMS 2004, Control Applications in Marine Systems*. Ancona, Italy 345-350.

Yaniv, O. and Horowitz, I. (1990) Quantitative Feedback Theory for Active Vibration Control Synthesis. *International Journal of Control* (51), 1251-1258.