CHAPTER 2

Interactive software tools for robust control: application to marine systems

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This work presents the main features of QFTIT and TIG two interactive software tool for robust control design using the QFT methodology. The main advantages of QFTIT and TIG compared to other existing tools are its ease of use and its interactive nature. These tools are freely available in the form of an executable file for Windows and Mac based platforms. In order to illustrate its use, this paper also includes an example; a robust controller is designed to stabilize the vertical movement of a high-speed ferry.

1 Introduction

Interactive tools are considered a great stimulus for developing the control engineering intuition. At present, a new generation of interactive software control packages have created an interesting alternative in comparison with the traditional approach. In this sense innovative and interesting ideas and concepts were implemented by Prof. Åström and coll. at Lund such as the concept of dynamic pictures and virtual interactive systems (Wittenmark et al., 1998). The main objective of these tools is to involve the users in a more active way in the analysis and design processes.

In essence, a dynamic picture is a collection of graphical windows that are manipulated simply by using the mouse. Users do not have to learn or write any sentences. If we change any active element in the graphical windows an immediate recalculation and presentation automatically begins. In this way we perceive how these modifications affect the result obtained.

These kinds of tools are based on objects that allow direct graphic manipulation. During these manipulations, the objects are immediately updated. Therefore the relationship among the objects is continuously maintained. Ictools and CCSdemo (Johansson et al., 1998) (Wittenmark et al., 1998) developed at the Department of Automatic Control at Lund Institute of Technology, and SysQuake at the Lausanne Federal Polytechnic School Automatics Institute (Piguet et al., 1999), are good examples of this new philosophy to produce a new family of interactive Computer-Aided Design (CAD) packages in automatic control.

Very often our work as control engineers is reduced to tune some design parameters using a trial and error procedure following an iterative process. Specifications of the problem are not normally used to calculate the value of the system parameters because there is not an explicit formula that connects them directly. This is the reason for dividing, each iteration, into two phases. The first one, often called synthesis, consists in calculating the unknown parameters of the system taking a group of design variables (which are related to the specifications) as a basis. During the second phase, called analysis, the performance of the system is evaluated and compared to the specifications. If they do not agree, the design variables are modified and a new iteration is performed (Dormido, 2004).

It is possible, however, to merge both phases into one and the resulting modification in the parameters produces an immediate effect. In this way, the design procedure becomes really dynamic and the users perceive the degree of change in the performance criteria given for the elements that they are manipulating. This interactive capacity allows us to identify much more easily the objectives that can be achieved (Dormido, 2003).

Interactive design with instantaneous performance display goes one step further. In many cases, it is not only possible to calculate the position of a graphic element (be it a curve, a pole, a template or a bound) from the model, controller or specifications, but also to calculate a new controller from the position of the element. For instance, a closed loop pole can be computed by calculating the roots of the characteristic polynomial, which itself is based on the plant and controller; and the controller parameters can be synthesised from the set of closed loop poles if some conditions on the degrees are fulfilled.

This two-way interaction between the graphic representation and the controller allows the manipulation of the graphical objects with a mouse in a very natural form. Since a good design usually involves multiple objectives using different representations (time domain or frequency domain), it is possible to display several graphic windows that can be updated simultaneously during the manipulation of the active elements.

The philosophy of interactive design with instantaneous performance display offers two main advantages when compared with the traditional procedure (non-interactive approach). In the first place, it introduces from the beginning the control engineer to a tight feedback loop of iterative design. The designers can identify the bottlenecks of their designs in a very easy way and can attempt to fix them. In second place, and this is probably even more important, not only is the effect of the manipulation of a design parameter displayed, but its direction and amplitude also become apparent. The control engineer learns quickly which parameter to use and how to push the design in the direction of fulfilling better tradeoffs in the specifications. Fundamental limitations of the system and the type of controller are therefore revealed (Åström 1994, 2000) giving way to finding an acceptable compromise between all the performance criteria. Using this interactive approach we can learn to recognise when a process is easy or difficult to control.

In this paper, such features of new interactive control tools are exploited in the field of Quantitative Feedback Theory as a "user-friendly" way to learn the main concepts, solve any non-trivial robust control problem, and gain experience of how Quantitative Feedback Theory (QFT) technique works. The focus has been on explaining the main features of Quantitative Feedback Theory Interactive Tool (QFTIT) (*http://ctb.dia.uned.es/asig/qftit/*) and Template Interactive Generator (TIG) (*http://ctb.dia.uned.es/asig/tig/*) and its role to encourage and help users understand the QFT technique. The constant increase in computing speed and power certainly makes that initial idea a real prospect.

QFT is a very useful robust control design methodology created by I. Horowitz (Horowitz, 1963). QFT uses frequency-domain concepts to satisfy performance specifications and to handle plant uncertainty. The basis of QFT relies on the observation that feedback is needed mainly when the plant is uncertain and/or when there are uncertain input disturbances acting on the plant. At the moment, and to the best of our knowledge, no fully interactive QFT tools are presently available.

QFT has been successfully applied to solve different control problems in various fields of engineering (Houpis et al., 2006). In the field of marine systems, QFT has been used in fast ferries to decrease the motion sickness incidence (Aranda et al., 2002a, 2002b, 2005a) (Cruz et al, 2004) (Díaz, 2005), to attenuate the roll movement (Aranda et al., 2004), and to control the lateral and longitudinal dynamics (Aranda et al., 2005b). Besides, QFT has been used in moored floating platform for dynamic positioning (Muñoz et al., 2006), and in hovercraft for tracking and stabilization (Aranda 2006a, 2006b).

The paper is organised as follows. In section 2 a brief description of the basic concepts of Quantitative Feedback Theory is included. Section 3 describes the main features of QFTIT and TIG. Section 4 includes an example to illustrate the use of these tools. A robust controller is designed to stabilize the vertical movement of a high-speed ferry. Finally, section 5 offers some conclusions.

2 Basic Concepts of QFT Methodology

The design procedure using QFT has been described in a wide variety of articles and books (Horowitz 1963, 1992, 2001) (Houpis et al., 2006) (Yaniv, 1999). QFT is a methodology used in the design of control systems including uncertainties in the plant which is subject to external disturbance in the input and output of the plant as well as measurement noise. Figure 1 illustrates the basic idea behind QFT applied to a SISO system with a control structure with two degrees of freedom. *F* is the transfer function of a pre-filter acting on the reference input *r*. *C* is the controller which, depending on an error signal *e*, generates a control signal *u* over the set of transfer functions of the plant *P*. This set describes the uncertainty region of the plant's parameters. *P* may be subject to disturbances at its input *v* and/or at its output *d*. *H* is the measure sensor of the output signal *y*, which may be affected by a measurement noise *n*.

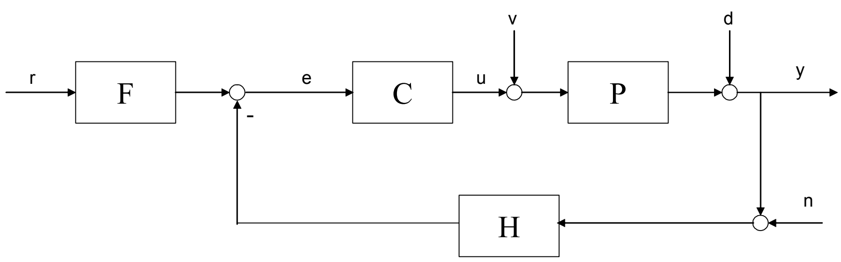

Fig. 1. Feedback System

The QFT method takes into consideration the quantitative information of the plant's uncertainty, robust operation requirements, robust tracking, expected disturbance amplitude and the associated damping requirement.

The controller *C* must be designed in such a way that the output variations *y*, which is a consequence of plant uncertainties *P*, is within specified tolerance boundaries. Furthermore, the effects of the disturbances *d* and *v* on the output must be acceptably small. On the other hand the pre-filter *F* is designed in order to perform the desired control of the reference signal *r*.

The design is performed using a Nichols diagram, defining a discreet set of trial frequencies Ω. This set is taken around the desired crossover frequency. As we are treating a family of plant instead of a single plant, the magnitude and phase of the plants in each frequency correspond to a set of points in the Nichols diagram. These sets of points form a connected region or a set of disconnected regions called “template”. $\mathcal{T}(\omega_i)$ denotes a template computed at the frequency $\omega_i \in \Omega$. A large template implies a greater uncertainty for a given frequency. The templates and the working specifications are used to define the domain bounds within the frequency domain. The domain bounds set the limit of the frequency response of the open loop system.

Each specification contains bound definitions. Bounds are calculated using the corresponding templates and specifications. The different types of bounds are calculated in the following way:

- *Stability bounds*. By using templates and the specified phase margin.
- *Control bounds*. By using templates and the upper and lower limits of the response in the frequency domain.
- *Disturbance bounds*. By using the disturbance refusal specifications.
- *Effort control bounds*. By using templates and the specified control limits.

All the bounds computed at the same frequency $\omega_i \in \Omega$, associated at the different specifications are intersecting to generate a final bound $B(\omega_i)$ which includes the most restrictive regions of all the considered bounds.

The controller is designed by means of a loop-shaping process in the Nichols diagram. This diagram sketches the intersection of the bounds calculated for each of the trial frequencies and the characteristics of the open loop nominal transfer function $L_0(j\omega)=C(j\omega)\cdot P_0(j\omega)$.

The design is carried out by adding gains, poles and zeroes to the frequency response of the nominal plant, in order to change the shape of the open loop transfer function. By doing so, the boundaries $B(\omega_i)$ are kept for each $\omega_i \in \Omega$. The controller is the set of all the aforementioned items (gain, poles and zeroes).

Should there be any specification which corresponds to the control of the reference signal, a pre-filter F must be used. This pre-filter is designed in a similar way as the controller, the difference being in the use of the limits imposed in the frequency response control. In this case, the shaping may be carried out in the Bode diagram instead of the Nichols diagram.

The last step for the QFT design is the analysis and validation which includes not only the analysis in the frequency domain but also the simulations in the temporary domain of the resulting closed loop system.

The benefits of QFT may be summarised as follows:

- The outcome is a robust controller design that is insensitive to plant variation
- There is only one design for the full envelope and it is not necessary to verify plants inside templates
- Any design limitations are clear at the very beginning
- There is less development time in comparison to other robust design techniques
- QFT generalises classical frequency-domain loop shaping concepts to cope with simultaneous specifications and plants with uncertainties
- The amount of feedback is adapted to the amount of plant and disturbance uncertainty and to the performance specifications
- The design trade-offs in every frequency are transparent between stability and performance specifications. It is possible to determine what specifications are achievable during the early stages in the design process
- The redesign of the controller for changes in the specifications can be done very fast.

3 Basic Features of the Interactive Tools QFTIT and TIG

3.1 QFTIT

QFTIT is an interactive software tool which implements the QFT methodology. It highlights for its interactive nature and easy-of-use (Díaz et al., 2005b). In QFTIT, all that the designer has to do is to place the mouse pointer over the different items (see Fig. 2.) which the tool displays on the screen. Any action carried out on the screen is immediately reflected on all the graphs generated and displayed by the tool. In this way the users can quickly see the effects of their actions during the design. QFTIT has been built on Sysquake (Piguet, 1999) and it implements in an only very interactive GUI all the stages of the QFT methodology. Therefore, it is very adequate to novice designer that wants to learn QFT. But, it can be used for advanced designer to solve real robust control problem with QFT (Díaz et al., 2005a). It is important to remark that QFTIT is freely distributed as an executable file for Windows and Mac platforms. It does not need to install additional programs, like Matlab, to run QFTIT.

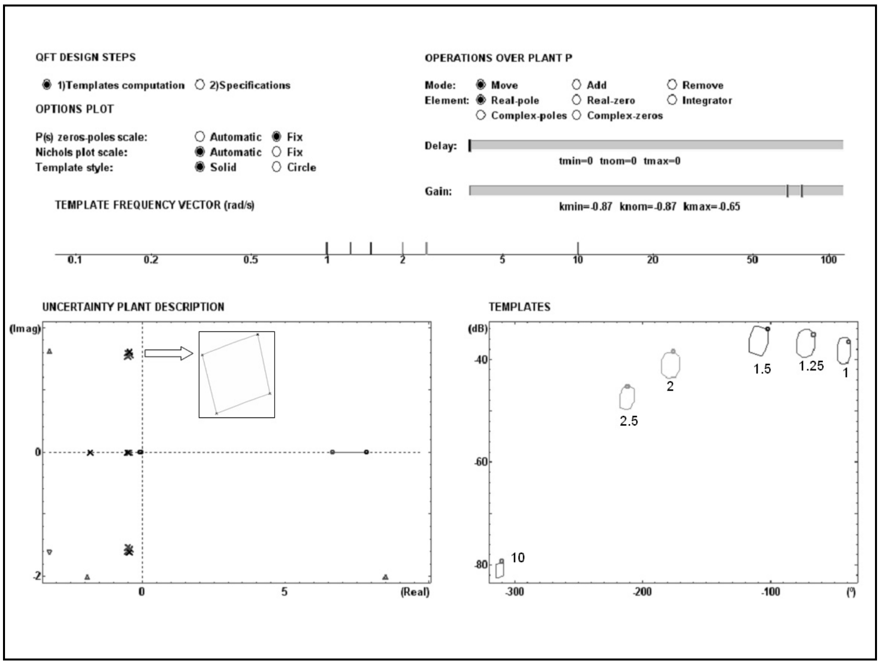

Fig. 2. Example of the QFTIT windows in the stage 1 (Templates computation)

The present version of QFTIT offers the user, amongst others, the chance of observing the changes instantly when some form of modification takes place in the available interactive objects:

- Variations produced in the templates when a change of the uncertainties of the different components of the plant or in the value of the template calculation frequency.
- Individual, grouped or intersected variation in the bounds as a result of the configuration of specifications, i.e., by adding zeroes and poles to the different specifications.
- The motion of the controller's zeroes and poles over the complex plane and the variation of its symbolic transfer function when the open loop transfer function is modified in the Nichols diagram.
- The change of shape of the open loop transfer function in the Nichols diagram and the variation of the expression of the controller's transfer function when any movement, addition or suppression of its zeroes or poles in the complex plane.

- The changes that take place in the temporary representation of the manipulated variable and in the controlled variable due to the variation of the nominal values of the different elements of the plant.
- The changes that take place in the temporary representation of the manipulated variable and of the controlled variable due to the introduction of a step perturbation in the input of the plant. The magnitude and the occurrence instant of the perturbation is configured by the user by means of the mouse.

Obviously, the present version of QFTIT has some limitations:

- It can only work with continuous SISO systems whose plant P is expressed in real factored form (RFF):

$$P(s)=\frac{K\cdot e^{-\tau s}\cdot\prod_{i=1}^{m}(s+z_i)\cdot\prod_{j=1}^{a}\left(s^2+2\cdot\delta_j\cdot\omega_{0j}+\omega_{0j}^2\right)}{s^N\cdot\prod_{l=1}^{n}(s+p_l)\cdot\prod_{q=1}^{b}\left(s^2+2\cdot\delta_q\cdot\omega_{0q}+\omega_{0q}^2\right)} \tag{1}$$

where K, τ, z_i, δ_j, ω_{0j}, p_i, δ_q, ω_{0q} are independent variables which can take the following uncertainty in their value:

$$K\in[K_{\min},K_{\max}]\subset\Re^{-}o\Re^{+} \tag{2}$$

$$\tau\in[\tau_{\min},\tau_{\max}]\subset\Re^{+} \tag{3}$$

$$\tau\in[\tau_{\min},\tau_{\max}]\subset\Re^{+} \tag{4}$$

$$z_i\in[z_{i\min},z_{i\max}]\subset\Re\quad i=1,\ldots,m \tag{5}$$

$$p_l\in[p_{l\min},z_{l\max}]\subset\Re\quad l=1,\ldots,n \tag{6}$$

$$\delta_j\in[\delta_{j\min},\delta_{j\max}]\subset\Re^{-}o\Re^{+}\quad j=1,\ldots.,a \tag{7}$$

$$\omega_{0j}\in[\omega_{0j\min},\omega_{0j\max}]\subset\Re^{+}\quad j=1,\ldots,a \tag{8}$$

$$\delta_q\in[\delta_{q\min},\delta_{q\max}]\subset\Re^{-}o\Re^{+}\quad q=1,\ldots.,b \tag{9}$$

$$\omega_q\in[\omega_{q\min},\omega_{q\max}]\subset\Re^{+}\quad q=1,\ldots,b \tag{10}$$

- According to this limitation, QFTIT only implements the algorithm by (Gutman et al., 1995) for the calculation of templates for RFF plants. The maximum number of templates which the tool can support in the current version is 10. However, this number can be modified without any difficulty.

· It only woks with frequency-domain specifications.

QFTIT implements the QFT design methodology by considering a maximum of five design stages:

1) *Templates computation*. During this stage, the user defines the plant (1), by configuring the uncertainty of its components. Furthermore, the user also selects the set of trial frequencies Ω.
2) *Specifications*. In this stage, the user selects and configures the specifications (see Table 2) that his/her design must fulfil. Each selected specification must configure the value of its associated W(s) and select the frequencies under which each specification must be verified. There is also a simultaneous generation, of associated bounds for each specification.
3) *Loop-shaping*. During this stage, the user performs the synthesis of the controller C(s) by shaping the open loop transfer function L0(s) in the Nichols diagram.
4) *Pre-filter design*. In this stage the user performs the synthesis of the pre-filter F(s) if the Type 6 2-DOF tracking specification has been previously activated by shaping of the minimum and maximum values of the closed loop transfer function in the Bode magnitude diagram.
5) *Validation*. In this stage the user makes sure that the specifications of his/her design are fulfilled.

When the user is working in a certain stage of the design, it is possible to advance on to the next stage or return to any of the previous stages. Readers who are interested can find a complete description of QFTIT in the User's Guide available at *http://ctb.dia.uned.es/asig/qftit/*

3.2 TIG

TIG assists the QFT designer in calculating template boundaries of interval plants, and plants with affine parametric uncertainty in their coefficients. These kinds of plants are very usual in control problems.

Let the following uncertain parameter vector be

$$p = [p_1, p_2, ..., p_L] \tag{11}$$

where pj $\in [p_j^{\min}, p_j^{\max}]$ j=1,2,..,L. With TIG it is possible to calculate the template boundaries of plants whose transfer functions have the following structure:

$$P(s;p) = \frac{b(s;p)}{a(s;p)} = \frac{\sum_{k=0}^{m} b_k(p) \cdot s^k}{\sum_{k=0}^{n} a_k(p) \cdot s^k} \tag{12}$$

where the coefficients $b_k(p)$ and $a_k(p)$ are linear combinations of the uncertain parameters, i.e.,

$$b_k(p) = \beta_{k0} + \sum_{j=1}^{L} \beta_{kj} \cdot p_j \tag{13}$$

$$a_k(p) = \alpha_{k0} + \sum_{j=1}^{L} \alpha_{kj} \cdot p_j \tag{14}$$

In the previous expressions β_{kj} and α_{kj} j=0,..,L are real constants. These kinds of plants are known as *plants with affine parametric uncertainty*.

A particular case of (12) is obtained when the plant transfer function coefficients are directly the uncertain parameters, such kinds of plants are known as *interval plants*:

$$P(s;q,r) = \frac{b(s;q)}{a(s;r)} = \frac{\sum_{k=0}^{m} q_k \cdot s^k}{\sum_{k=0}^{n} r_k \cdot s^k} \tag{15}$$

where $q_k \in [q_k^{\min}, q_k^{\max}]$ and $r_k \in [r_k^{\min}, r_k^{\max}]$.

For the plants described by (12) and (15), TIG includes four algorithms to calculate the associated templates. These algorithms are the following: a) the Bailey & Hui algorithm (Bailey and Hui, 1989), b) the Fu algorithm (Fu, 1990), c) the Kharitonov segment algorithm (Bartlet, 1993), and d) the grid algorithm.

Besides, TIG can also find the template boundaries associated with other kinds of plants whose templates have been previously computed in Matlab. Thus, TIG is able to cooperatively work with other software tools, like Matlab QFT Frequency Domain Control Design Toolbox (Borghesani et al., 1995) and QFTIT. In fact, TIG was developed to increase the kind of plants which can be used in QFTIT (the present version of QFTIT only works with plants expressed in RFF).

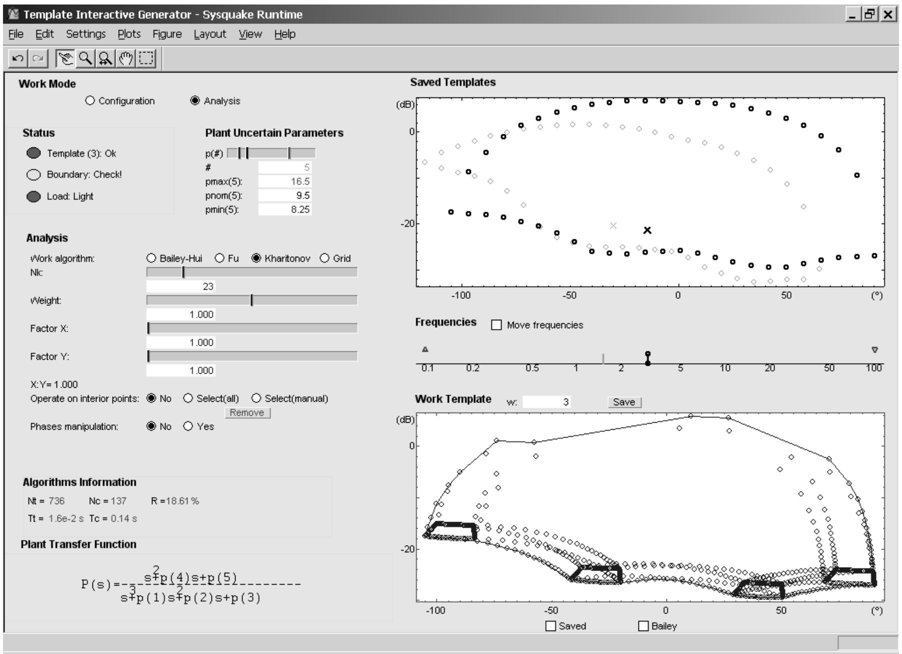

Fig. 3. Example of the TIG window in the Analysis mode

Like QFTIT, the main features of TIG are its ease of use and strong interactivity. These are common characteristics of all the software tools developed with the program SysQuake. Some examples of TIG interactivity are:

- The work template $\Gamma_w(\omega_w)$ (see Fig. 3.) in the Nichols chart (or on the complex plane) is simultaneously modified if users change the configuration parameter of the template computation algorithm or the work frequency ω_k.
- The boundary of the work template $\Gamma_w(\omega_w)$ in the Nichols chart (or on the complex plane) is simultaneously modified if users change the configuration parameter of the ε-algorithm (Montoya, 1998) used for computing the boundary template.

Other TIG features are:

- The simultaneous visualization of the work templates computed for each of the four template computation algorithms implemented in TIG.

- The automatic selection and removing of all $\Gamma_w(\omega_w)$ internal points.
- The manual selection and removing of any $\Gamma_w(\omega_w)$ point.

With TIG it is possible to work in two different modes: configuration and analysis. The configuration mode consists of four sequential steps:

- Step 1. Configuration of the plant uncertain parameters.
- Step 2. Configuration of the plant transfer function denominator.
- Step 3. Configuration of the plant transfer function numerator..
- Step 4. Configuration of the work frequencies set Ω.

Furthermore, in the analysis mode, users can do, among other things, the actions previously described. Readers who are interested can find a complete description in the User's Guide available at *http://ctb.dia.uned.es/asig/tig/*.

4 Illustrative Example: Stabilization of the Vertical Movement on a High-speed Ferry

4.2 Problem Statement

In a first approximation, the vertical acceleration of a high speed ferry is only associated with the pitch motion. Continuous linear models of the vertical dynamics of a high-speed ferry were identified (Aranda et al., 2004) for different navigation speeds (20, 30 and 40 knots). Based in this models, a family of plants $\mathcal{P}$ defined as a transfer function (output: pitch motion, input: position of the actuator (T-Foil)) with parametric uncertainties in its coefficients was obtained in (Díaz, 2002):

$$\mathcal{P} = \left\{ \begin{array}{ll} P(s) = \dfrac{K(s+a)\cdot(s+b)}{(s+103.2)\cdot(s+1.8)\cdot(s+c)\cdot(s^2+ds+e)} & \\ & \\ K \in [-0.87, -0.65] & a \in [-7.85, -6.67] \\ b \in [0.026, 0.042] & c \in [0.44, 0.49] \\ d \in [0.86, 0.97] & e \in [2.59, 2.80] \end{array} \right\} \quad (16)$$

The nominal plant is:

$$P_0(s) = \frac{-0.87(s-7.85)(s+0.042)}{(s+103.2)(s+1.8)(s^2+0.86s+2.8)} \quad (17)$$

A decrease in pitch motion is equivalent to reducing the system's sensitivity to the waves. From the point of view of frequency domain this means working with the sensitivity function S of the output (pitch) y to the perturbation (waves) d

$$S(s) = \frac{y(s)}{d(s)} = \frac{1}{1 + P(s) \cdot C(s)} \tag{18}$$

A controller C must be designed, so that for all $P \in \mathcal{P}$ the system is stable

$$\left| \frac{C(j\omega) \cdot P(j\omega)}{1 + C(j\omega) \cdot P(j\omega)} \right| \leq 1.2 \qquad \forall P \in \mathcal{P} \quad \forall \omega \in [0, \infty) \tag{19}$$

and for all disturbance $d \in D$ and frequency $\omega \in \Omega = [1, 2.5]$ (rad/s) the magnitude of the sensitivity function S is bounded by the specification

$$|S(j\omega)| \leq W_d(\omega) \qquad \forall P \in \mathcal{P} \quad \forall \omega \in [1, 2.5] \tag{20}$$

where $W_d(\omega)$ is given in Table 1.

Table 1. Specification $W_d(\omega)$

ω [rad/sec]	$W_d(\omega)$ [dB]
1.00	-0.14
1.25	-0.21
1.50	-0.60
2.00	-0.75
2.50	-0.28

QFTIT will be used to solve this problem. Because the family of plants is given in RFF, it is not necessary to use TIG.

4.2 Stage 1: Template Computation

According to the disturbance rejection specification (see Table 1) and the robust stability specification (19), a possible set of trial frequencies is

$$\Omega_1 = \{1, 1.25, 1.5, 2,, 2.5, 10\} \quad (rad/s) \tag{21}$$

The frequencies Ω_1 can be introduced in QFTIT using its area *Template frequency vector* (see Fig. 2). There is a horizontal axis ω representing radian per seconds. It is possible to add, remove and change the frequencies of Ω_1. Each of these frequencies is represented by a vertical segment with an associated colour code that can be moved along the ω axis.

In this problem, the elements of the plant (16) are a gain, two simple zeroes, three simple poles and a pair of complex poles. One possible way of introducing them into QFTIT is using their areas *Operations over plant P* and *Uncertainty plant description*.

The area *Operations over plant P* is used to select the type of plant element (real-pole, real-zero, complex-pole, complex-zero, integrator) on which we want to perform some type of action (move, add or remove) in the *Uncertainty plant description* area. It is also possible to configure each element by using two sliders: the uncertainty of the delay and the gain of the plant, i.e. the specification of the minimum, maximum and nominal values. For the plant (16) the slider associated with the gain would have to be moved in order to configure its minimum value k_{min}= -0.87, its maximum value k_{max}=-0.65 and its nominal value k_{nom}=-0.87.

The *Uncertainty plant description* area is used to graphically design the configuration of the uncertainty of the plant poles and zeroes. This operation is carried out with the use of the mouse over the selected pole or zero element. For simple zeroes or poles the uncertainty is represented by a segment, whilst for complex zeroes and poles it is represented by a circular sector limited by the maximum and minimum values of the damping factor and the natural frequency of each complex item (pole or zero). Both representations include the extreme values as well as the nominal value.

For this problem, according to the plant defined in (16), by selecting the adequate options in the *Operations over plant P* area, it would be possible to add two simple zeroes (s=-a, s=-b), three simple poles (s=-103.2, s=-1.8, s=-c) and a pair of complex poles ($s = -d \pm j \cdot \sqrt{d^2 - 4 \cdot e}$) in the Uncertainty plant description area and to configure the uncertainty (a, b, c, d, e) of these elements and their nominal values (17) by dragging the mouse.

The area *Templates* shows a Nichols diagram that includes six templates calculated for the set of frequencies defined in Ω_1.

4.3 Stage 2: Specifications

In this problem there are two specifications: robust stability specification (19) (Type 1) and disturbance rejection at plant output (20) (Type 2). If

Type 1 specification is selected and activated in the *Specification type zone*, then it is possible to configure the value of the constant W_s by simply dragging the slider from value 1 to the desired value 1.2. Just under the slider there is a display showing the value of the gain margin ($GM \geq 1.8$) and the phase margin ($PM \geq 49.2^o$) obtained. It is also possible to view simultaneously and interactively how the specification modulus is being modified in the Bode diagram and how the associated bounds change in the Nichols diagram.

The specification of disturbance rejection at plant output (Type 2) for this problem (see Table 1) is given as a vector whose components are the values that the specification must take in dB at different frequencies. These kinds of specifications are called Point-to-Point (PP) in QFTIT. Thus, the configuration of this specification given in Table 1 is as follows: first, it is necessary to select and activate the *Type 2* specification in the *Specification type zone*. Second, it is necessary to select the PP mode in the *W(s) frequency-domain* specification zone. The *W(s) magnitude specification* zone displays circles in different colours placed in the trial frequencies of the specification and with a value of 0 dB. Users can configure by dragging the mouse pointer over the modulus points to the chosen value. This will simultaneously update the bounds associated with this specification in the Nichols.

In QFTIT the final bounds $B(\omega_i)$ $\omega_i \in \Omega_1$ associated at the intersection of the two configured specifications are immediately displayed in the *Nichols Plot* zone by selecting the option *Intersection* in the *Option plot* zone.

4.4 Stage 3: Loop Shaping

During this stage, the user performs the synthesis of the controller $C(s)$ in the Nichols diagram by shaping the open loop transfer function L_0 in order to maintain the boundaries $B(\omega_i)$ $\omega_i \in \Omega_1$. The main manipulation that the user can perform within this area of the programme is the displacement of L_0 in certain directions depending on the selected controller item in the *Operations Over Controller C* zone.

The changes made to L_0 in the Nichols diagram are immediately reflected in an interactive way on the zeroes-poles map corresponding to C(s) as well as in the symbolic expression of the transfer function. Likewise, the interactions performed by the user on the zeroes-poles map of the controller will be reflected in the Nichols diagram. Thus, the user has a very interactive and flexible tool to perform the synthesis of the controller.

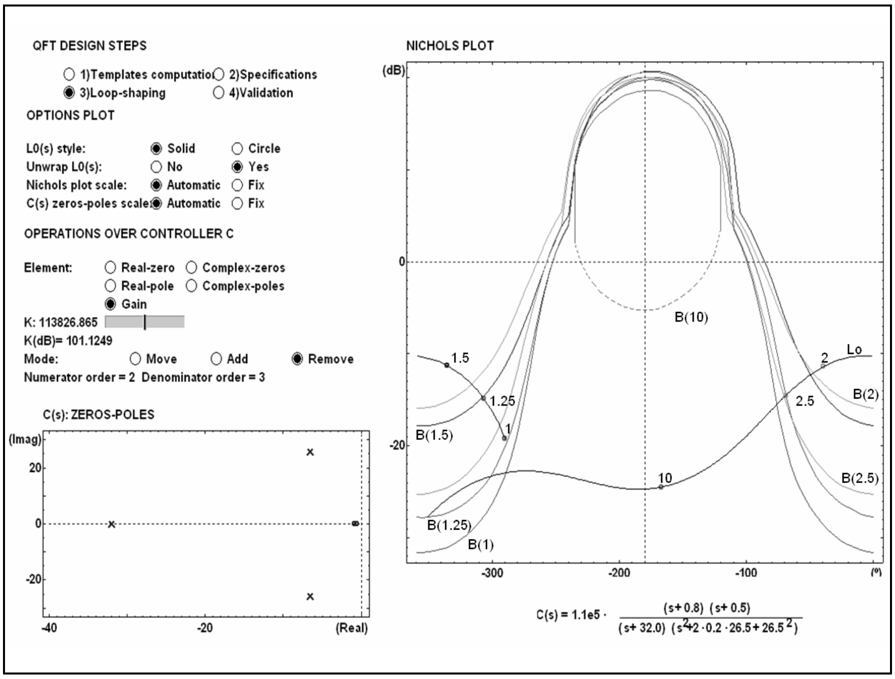

Fig. 4. Aspect of the QFTIT window after designing the controller *C*

Figure 4 displays the aspect of the QFTIT window after the Loop-Shaping stage. The Nichols diagram shows the intersection of the bounds associated with the established specifications and the final L_0. It can be observed how the points $L_0(j\omega_i)$ fulfil the boundaries $B(\omega_i)$ $\omega_i \in \Omega_1$.

The expression of the designed controller is:

$$C(s) = 1.1 \cdot 10^5 \cdot \frac{(s+0.5)\cdot(s+0.8)}{(s+32)\cdot\left(s^2 + 2 \cdot 0.2 \cdot 26.5 \cdot s + 26.5^2\right)} \tag{22}$$

It is a controller with two real zeroes, one real pole and a pair of complex poles. The zeroes and the poles of $C(s)$ are represented in the *C(s): Zeros-Poles* zone.

4.5 Stage 4: Validation

During this stage designers make sure that the specifications of their design are fulfilled. The user only has to select the type of specification to validate, and QFTIT immediately shows the modulus of W_{si} and the worst case modulus of the associated characteristic function of the system in a Bode magnitude diagram.

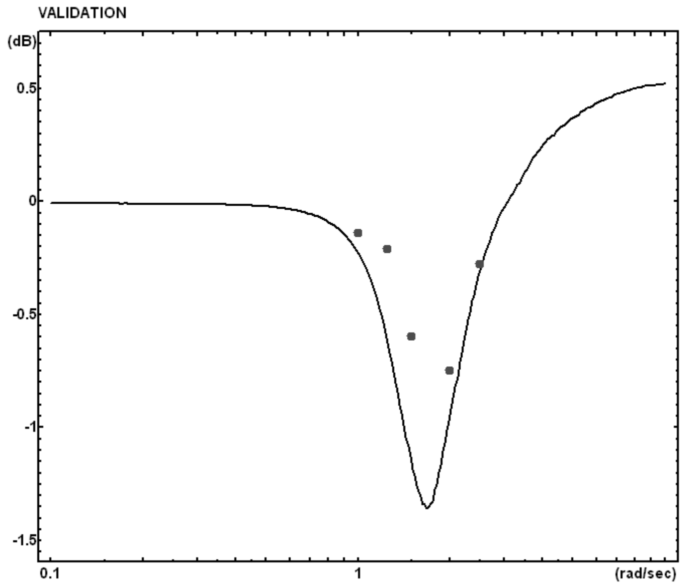

Fig. 5. Maximum magnitude in dB of the maximum magnitude of the sensitivity function $max\{|S(j\omega)|\}$ (solid line) and $W_d(\omega)$ (circles).

For this, two specifications have to be validated: disturbance rejection at plant output (20) and robust stability (19). Figure 5 displays $W_d(\omega)$ (circles) and the maximum magnitude of the sensitivity function $max\{|S(j\omega)|\}$ (solid line). It can be observed how the specification of disturbance rejection at plant output (20) is fulfilled, since $max\{|S(j\omega)|\}$ is below $W_d(\omega)$ in the design range of frequencies Ω=[1,2.5] (rad/s).

On the other hand, Figure 6 shows the maximum magnitude in dB of the closed-loop transfer function $max\{|L(j\omega)/(1+L(j\omega))|\}$ and the constant gain line W_s=1.2 (1.58 dB). As $max\{|L(j\omega)/(1+L(j\omega))|\}$ does not surpass the horizontal line in any of the frequencies, the robust stability specification would be correct with the controller C designed during step 3. This design assures a phase margin $PM \geq 50°$ and a gain margin $GM \geq 1.8$.

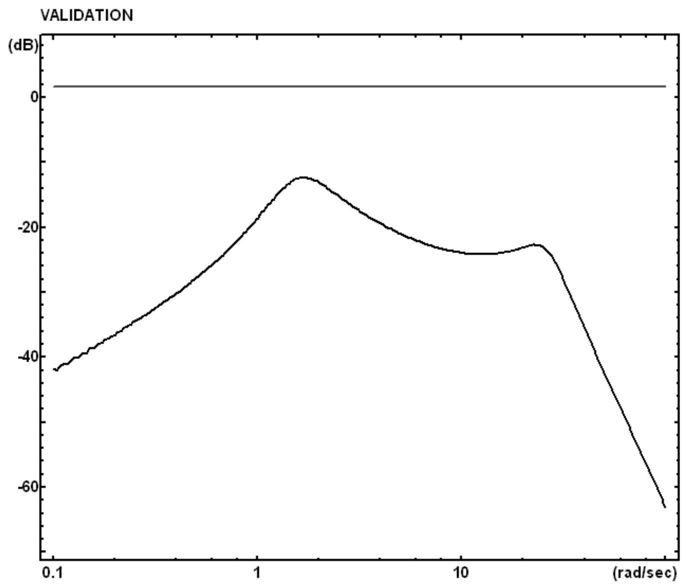

Fig. 6. Maximum magnitude in dB of the closed-loop transfer function $max\{|L(j\omega)/(1+L(j\omega))|\}$ and the constant gain line W_s=1.2 (1.58 dB).

Finally, time simulation was done using the controller (22) at four working points (ship speed U=30, 40 knots and sea state number SSN= 4, 5) The designed controller ensures a decrease around 10.9 % of the vertical acceleration associated to the pitch motion.

5 Conclusions

This paper has described the basic features of the software tools QFTIT and TIG for the design of robust controllers by means of the QFT methodology. The main features of these tools are its ease of use and its strong interactivity. Any action carried out on the screen by users is immediately reflected on all the graphs generated and displayed by the tool. This allows users to visually perceive the effects of their actions. Both of these tools are freely available as executable files for Windows or Mac platforms.

Besides, this paper has shown the utility of these tools for solving robust control problem in marine systems. A robust controller has been designed to stabilize the vertical movement of a high-speed ferry.

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