

An Interactive Software Tool for Learning Robust Control Design Using Quantitative Feedback Theory Methodology*

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We present the main features of Quantitative Feedback Theory Interactive Tool (QFTIT) a new interactive software tool for robust control design using the Quantitative Feedback Theory (QFT) methodology. The main advantages of QFTIT compared to other programs are its ease of use and its interactive nature. All that the end-user has to do is to place the mouse pointer over the different items which the tool displays on the screen. Any actions carried out on the screen are immediately reflected in all the graphs generated and displayed by the tool. This allows users to perceive the effects of their actions during the design of the controller. QFTIT has been designed bearing in mind the needs of beginners who want to learn the QFT methodology as well as the needs of advanced users. The tool is freely available in the form of an executable file for Windows or Mac-based platforms. In this paper, a robust control problem is solved with QFTIT in order to demonstrate the tool.

Keywords: quantitative feedback theory (QFT); robust control; control systems computer-aided design (CSCAD); educational software

INTRODUCTION

IN THE 1990s, the spectacular increase in the use of personal computers led to the development of new software for very different areas. In automatic control, MATLAB is without doubt the most important software tool. It has a broad set of library functions, ‘toolboxes’ to implement different control techniques. In order to use these library functions, users have to write a script file. Users must, therefore, have a basic programming knowledge. Once the script has been written, the next step is to execute it from the MATLAB command line and wait for the results. If users want to change some parameter of their design, they must change some line of script code. Obviously, this way of working is rather tedious.

From the end of the 1990s it has been possible to build graphic user interfaces (GUIs) with MATLAB, which allow its functions to be executed without writing any line of code. Many of the toolboxes already include these GUIs as an alternative way of working. Basically, the only thing users have to do is to fill some blank fields with the parameter values and press some button to start the computation. Moreover, with the MATLAB GUI the mouse pointer can drag some graphic element in just one plot.

There are thus two ways of working with the MATLAB toolboxes:

1. Writing a script file and invoking it from the MATLAB command line.
2. Using a GUI.

These are considered as the *traditional approach* to analysing a system or designing a controller.

A new generation of interactive software control packages now makes possible an interactive design with instantaneous performance display. They have created an interesting alternative, called *interactive approach*. Innovative and interesting ideas and concepts have been implemented by Professor Åström and colleagues at Lund Institute of Technology, such as *dynamic pictures* and *virtual interactive systems* [1]. 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.

These kinds of tools are based on objects that allow direct graphic manipulation. During these manipulations, all the objects are immediately updated, not only as in the MATLAB GUI. Therefore, the relationship among the objects is continuously maintained. *Ictools* and *CCSdemo* [2, 1] developed at the Department of Automatic Control at Lund Institute of Technology,

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SysQuake at the Lausanne Federal Polytechnic School Automatics Institute [3, 4], and *Easy Java Simulation* developed at the Department of Mathematics at the University of Murcia [5, 6] are good examples of this new philosophy for producing a new family of interactive computer-aided design packages in automatic control systems.

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 [7].

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 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 [8, 9].

The interactive approach 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; also the controller parameters can be synthesised from the set of closed loop poles if some conditions on the degrees are fulfilled [10].

This two-way interaction between the graphic representation and the controller allows the manipulation of graphical objects with a mouse. 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.

This interactive philosophy offers two main advantages over the more traditional approach. In the first place, it introduces the control engineer from the beginning to a tight feedback loop of iterative design. Designers can identify the bottlenecks of their designs in a very easy way and can attempt to fix them. Second, 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 [11, 12] 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.

Quantitative Feedback Theory (QFT) is a very versatile control design technique. It can be used in linear or non-linear systems, invariant or variant time systems, continuous or discrete systems, and Single Input—Single Output (SISO) or Multiple Input—Multiple Output (MIMO) systems [13, 14, 15, 16, 17, 18]. Moreover, it is possible to use QFT on non-minimum phase systems and time-delay systems.

One additional very attractive feature of the QFT technique is the fact that it generates narrow bandwidth controllers, unlike other robust control techniques (H_∞ , μ synthesis, LQG/LTR). Furthermore, QFT usually leads to lower order controllers than other robust control techniques. QFT also deals non-conservatively with parametric, non-parametric and mixed uncertainty models. It does not assume special structures for plant uncertainties, disturbances and specifications such as norm-bounded uncertainties, etc.

On the other hand, the speed at which a QFT design can be performed depends to a great extent on user experience, while other robust control techniques are less user dependent. Accordingly, QFTIT, thanks to its ease of use and interactive nature, helps engineers and designers to quickly learn and understand it.

Besides, QFTIT can also be used for advanced users to solve robust control problems. In fact, in [19] QFTIT was successfully used for designing a monovariable robust regulator for the reduction of motion sickness incidence on a high-speed ferry.

A robust control problem proposed in [20] describes the educational application of QFTIT.

BASIC CONCEPTS OF QUANTITATIVE FEEDBACK THEORY

The design procedure using QFT has been described in a wide variety of articles and books [13, 14, 15, 16, 17, 18]. QFT is a methodology used in the design of control systems including uncertainties in the plant which is subject to external disturbance in its input and output as well as to measurement noise. Figure 1 illustrates the basic idea behind QFT applied to a SISO system with a control structure having 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 .

The QFT method takes into consideration quantitative information about 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 are a consequence of plant uncertainties P , are 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 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 intersect to generate a final bound $\mathcal{B}(\omega_i)$ 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 $\mathcal{B}(\omega_i)$ 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 signals, 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 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 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.

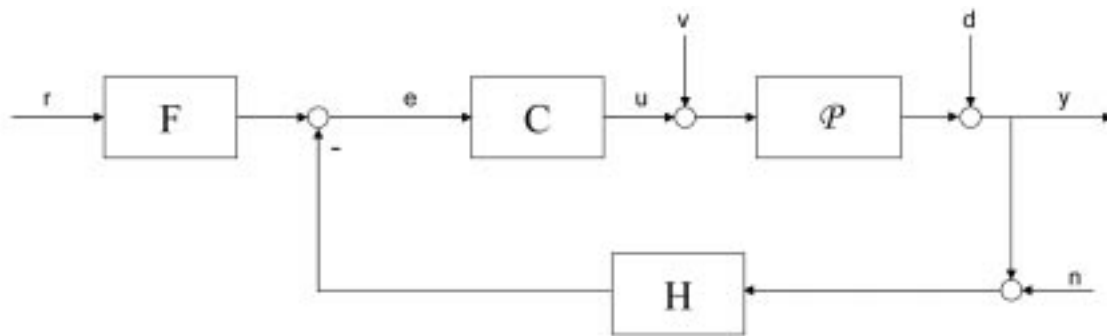


Fig. 1. Feedback System

- 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.

MAIN FEATURES OF THE QFTIT INTERACTIVE TOOL

There are currently many different CAD tools [21, 22, 23, 24, 25] all aimed at helping the designer implement the different stages of QFT methodology. These tools will typically be implemented as a set of MATLAB functions which can be used to write scripts in accordance with the design problem that needs to be solved. Thus, these tools require that the designer should not only have a knowledge of robust control but also some type of programming experience.

On the other hand, the majority of these tools contain small graphic interactive programs based on MATLAB GUI which are quite easy to use. These programs have been created especially for the controller synthesis stage (loop shaping) and the pre-filter synthesis. However, the interaction of these programs is reduced to either a simple interaction with a single graph, normally the Nichols diagram or filling out the fields in a dialogue box in order to configure the values of certain parameters and continue with the different stages of the design.

The most well known of all the existing CAD tools is, without a doubt, the QFT Frequency Domain Control Design Toolbox (FDCDT) written in MATLAB by Borghesani, Chait and Yaniv [22]. At present, FDCDT is more powerful than QFTIT, as its goal falls beyond our scope. Table 1 briefly compares both tools while highlighting the differences between them, mainly those related to interactivity and ease-of-use.

Thus the main difference between both tools is *interactivity*. Other differences between both tools are that FDCDT requires the installation of Matlab. It thus offers more flexibility than QFTIT, but it is also more difficult to use. On

the other hand, QFTIT is freely available (<http://ctb.dia.uned.es/asig/qftit/>) and can run under Windows or Mac, without requiring any kind of programming to build an example (only mouse operations or text insertion in dialogue boxes have to be performed). In this way, the effort is focused on understanding the fundamental concepts of the QFT technique without writing a line of code, allowing the user to analyse interactively the effect that the modification of any plant/controller parameter has on the stability of the closed-loop system and performance specifications, without requiring the planning of iterative simulations. Therefore, with QFTIT the user is very quickly visually aware of the effects of his/her actions during the design.

Advantages of QFTIT

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

1. 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.
2. 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.
3. 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.
4. 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.
5. 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.
6. 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.

Further possibilities offered by QFTIT are:

7. Display of the points used in the sketch of the open loop transfer function in the Nichols diagram during the loop-shaping stage.
8. Display of the points used to sketch the maximum and minimum values of the closed loop transfer function in the Bode magnitude diagram during the pre-filter design stage.

Table 1. QFTIT versus FDCDT in terms of ease-of-use and interactivity

Main features of the tools	QFTIT	FDCDT
Free availability	Yes	No
Requires other packages (like Matlab)	No	Yes
Requires additional programming	No	Yes
Open source code	No	Yes
Interactive plant definition	Yes	No
Interactive template computation	Yes	No
Interactive specification definition	Yes	No
Interactive loop-shaping	Yes	Yes
Interactive pre-filter design	Yes	Yes
Interactive validation	Yes	No

9. Display of the points used to sketch the most unfavourable case of the system's characteristic function in the Bode magnitude diagram subject to validation and dependent of the selected type of specification. It is also possible to emphasise the points in the curve associated to the frequencies for which there are corresponding specifications. This feature helps the user to assess if the specification is being fulfilled. This display takes place during the validation stage.

Current limitations of QFTIT

Obviously, the present version of QFTIT has some limitations:

- (a) *Analysis and design of SISO systems.* One of the most important limitations of the tool is that it can only work with continuous SISO systems whose plant P is expressed in real factored form as follows:

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

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

$$K \in [K_{\min}, K_{\max}] \subset \mathbb{R}^- \circ \mathbb{R}^+ \quad (2)$$

$$\tau \in [\tau_{\min}, \tau_{\max}] \subset \mathbb{R}^+ \quad (3)$$

$$z_i \in [z_{i\min}, z_{i\max}] \subset \mathbb{R} \quad i = 1, \dots, m \quad (4)$$

$$p_l \in [p_{l\min}, p_{l\max}] \subset \mathbb{R} \quad l = 1, \dots, n \quad (5)$$

$$\delta_j \in [\delta_{j\min}, \delta_{j\max}] \subset \mathbb{R}^- \circ \mathbb{R}^+ \quad j = 1, \dots, a \quad (6)$$

$$\omega_{0j} \in [\omega_{0j\min}, \omega_{0j\max}] \subset \mathbb{R}^+ \quad j = 1, \dots, \quad (7)$$

$$\delta_q \in [\delta_{q\min}, \delta_{q\max}] \subset \mathbb{R}^- \circ \mathbb{R}^+ \quad q = 1, \dots, b \quad (8)$$

$$\omega_{0q} \in [\omega_{0q\min}, \omega_{0q\max}] \subset \mathbb{R}^+ \quad q = 1, \dots, b \quad (9)$$

- (b) *Templates calculation.* QFTIT only implements the algorithm by Gutman, Baril and Neuman [26] for the calculation of templates. The maximum number of templates N_T which the tool can support in the current version is 10.
- (c) *Specifications.* The number of specifications in the frequency domain is also restricted (see Table 2). The types of specifications implemented in QFTIT are similar to the FDCDT specifications [22]. In Table 2, W_{si} , $i = 1, \dots, 6$, represents either a transform function or a vector where each of the elements is a certain value expressed in decibels for a given frequency.

HOW TO USE THE QFTIT INTERACTIVE TOOL

A detailed description of QFTIT with several examples of robust control design using QFT

methodology may be obtained from the tool's user guide available at <http://ctb.dia.uned.es/asig/qftit/>

Tool layout

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 .

$$\Omega = \{\omega_1, \omega_2, \dots, \omega_N\} \quad N \leq N_T \quad (10)$$

The templates $\mathcal{T}(\omega_i)\omega_i \in \Omega$ are simultaneously computed and shown while user performs these actions.

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 $L_0(s)$ 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 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. Figure 2 shows these transitions.

Description of the design stages: items and interactivity

The description of the different types of items displayed by the tool as well as the interaction amongst them depending on the design stage will be done by means of an illustrative design example. A variation of one of the robust control problems proposed in [20]. Let the family of plants:

$$\mathcal{P} = \left\{ P(s) = \frac{K}{s \cdot (s + a)} \quad K \in [1, 10], a \in [1, 10] \right\} \quad (11)$$

Considering the nominal values $K_{nom} = 9$ and $a_{nom} = 8$. The specifications that the system must fulfil are:

- (a) *Type 1: Robust Stability.* The desired phase

margin is $PM \geq 49.25^\circ$. An equation that relates PM with W_{s1} is given in [18]:

$$PM = 180^\circ - \frac{180^\circ}{\pi} \arccos\left(\frac{0.5}{W_{s1}^2}\right) \quad (12)$$

Clearing the previous expression yields $W_{s1} = 1.2\forall\omega \geq 0$.

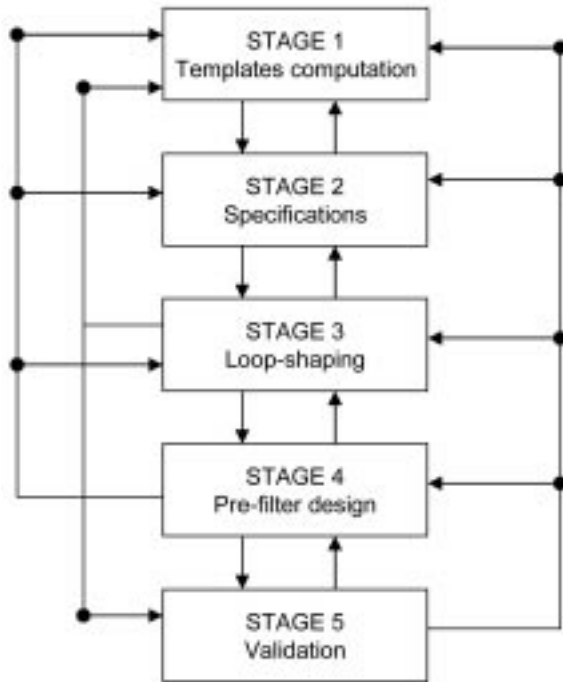


Fig. 2. Stage transitions in QFTIT

(b) Type 6: 2-DOF tracking.

$$W_{s6a}(s) = \frac{0.7 \cdot (s + 30)}{s^2 + 2 \cdot 0.45 \cdot 4.44 \cdot s + (4.44)^2}$$

$$W_{s6b}(s) = \frac{120}{(s + 3)(s + 4)(s + 10)} \quad \forall \omega \in [0, 15] \quad (13)$$

The set of trial frequencies considered is:

$$\Omega = \{0.1, 0.5, 1, 2, 15, 100\} \quad (14)$$

The robust control problem consists in designing an adequate controller $C(s)$ and pre-filter $F(s)$ in order for the closed loop system fulfilled the specifications.

Stage 1: Templates computation. In this stage of the design the display of the tool (see Fig. 3) shows seven distinct areas: QFT design steps, Options plot, Template frequency vector, Uncertainty plant description, Operations over plant P, Templates and Status bar.

In the QFT design steps area the user has access to radio buttons which are associated with every previous design stage, as well as the present stage and the next stage. The present design stage is characterised by the activation of its associated radio button. The user can select in the *Options plot* area different graphic options associated with the figures shown in the windows, such as the scaling types (automatic or fixed) and the type of line (solid or circle).

In the Template frequency vector area the user may configure the frequencies for the calculation of the templates. There is a horizontal axis ω

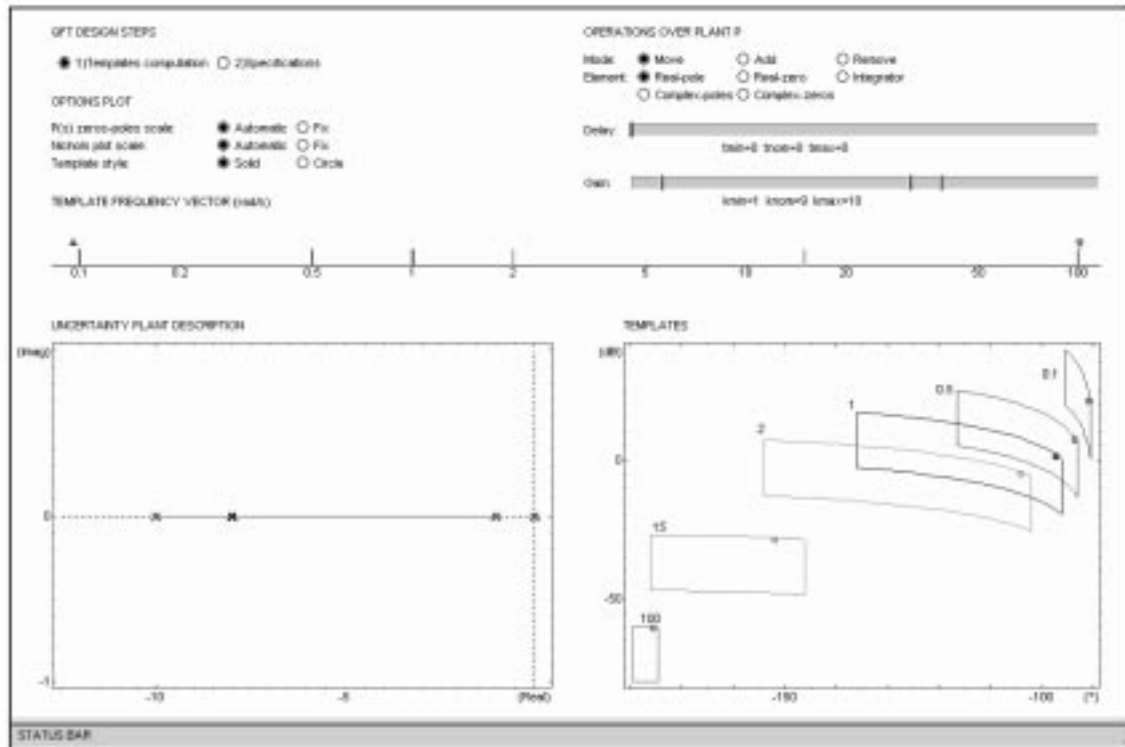


Fig. 3. Stage 1 Templates computation of the proposed example

representing radians per seconds. It is possible to add, remove and change the frequencies of the trial set Ω . Each of these frequencies is represented by a vertical segment with an associated colour code which can be moved along the ω axis. For the proposed example six frequencies must be added according to (14).

The Operations over plant P area is used to select the type of element of the plant (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 it by using two sliders: the uncertainty of the delay and the uncertainty of the gain of the plant, i.e. the specification of the minimum, maximum and nominal values. For the proposed example the slider associated with the gain of the plant would have to be moved in order to configure its minimum value $k_{min} = 1$, its maximum value $k_{max} = 10$ and its nominal value $k_{nom} = 9$.

The Uncertainty plant description area is used to design the configuration of the uncertainties of the poles and zeroes of the plant. This operation is carried out with the use of the mouse over the selected pole or zero element. Figure 4 shows an example of how the uncertainty is represented for the different types of possible elements of a plant. For the case of simple zeroes or poles the uncertainty is represented by a segment, whilst in the case of complex zeroes and poles it is represented by a circular sector limited by the maximum and minimum values of the damping factor and of the natural frequency of each complex item (pole or zero). Both representations include the extreme values as well as the nominal value.

In the proposed example, the elements of the plant (11) are the gain, which has already been configured in the Operations over plant P area, an integrator and a simple pole which includes uncertainty. By selecting the adequate options here, it is possible to add in the Uncertainty plant descrip-

tion area an integrator, and to configure it by dragging with the mouse the uncertainty of the real pole $a \in [1,10]$ and its nominal value $a_{nom} = 8$. Figure 3 above shows the final configuration of this area for the proposed example.

The Templates area shows a Nichols diagram that includes the calculated templates $\mathcal{T}(\omega_i) \in \Omega$. For the given example, Fig. 3 shows in the Templates area six templates according to (14). The templates are instantly recalculated each time one of the following items is changed:

- The uncertainty of the zeroes and poles of the plant in Uncertainty plant description.
- The gain of the plant in Operations over plant P .
- The set Ω in Template frequency vector.

The Status bar area displays different types of messages and information depending on the position of the mouse pointer within the window. For example, if the mouse pointer were to be situated over an item of the plant in the Uncertainty plant description zone, the maximum, minimum and nominal value would be displayed in the Status bar.

Stage 2: Specifications. During the input of specifications stage the display of the tool (see Fig. 5) shows six distinct new zones: Specification types, $W(s)$ frequency-domain specification, Specification frequency vector, $W(s)$: zeros-poles, $W(s)$: magnitude specification and Nichols plot.

The user can select the type of specification (see Table 2) as well as their state (on/off) in the Specification types area. For the proposed example, the specifications Type 1: Robust stability and Type 6: 2-DOF tracking must be selected.

In the $W(s)$ frequency-domain specification zone the user can select the different types of options for the configuration of the active specification. For example, the user can select the implementation mode (*work*). In the mode (TF) the

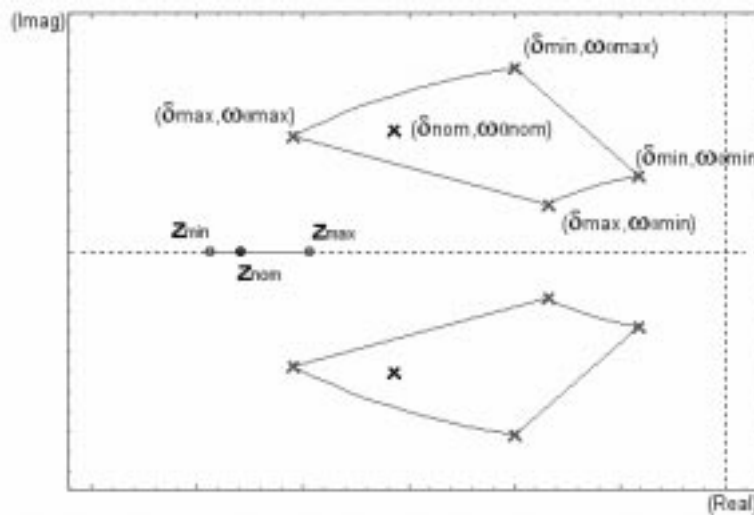


Fig. 4. Uncertainty of the elements of the plant in QFTIT

specification is defined as a transfer function while in the mode (PP) the specification is given as a vector in decibels.

It is also possible to select the type of element of the transfer function $W(s)$ (real-pole, real-zero, complex-pole, complex-zero, integrator) on which we want to execute a certain action (move, add or remove) within the $W(s)$: Zeros-Poles zone. Furthermore, the user can configure by means of a slider the value of the gain $W(s)$. In the proposed example, if type 1 specification is selected and activated in the Specification types zone, then it is possible to configure the value of the constant W_{s1} by simply dragging the slider from the value 1 to the desired value 1.2. Just under the slider there is a display showing the value of the gain margin and the phase margin 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 frequency vector zone displays a horizontal axis ω graded in radians per second. On this axis there are vertical segments of different colours situated in the frequencies for which the templates have been calculated in stage 1. This allows the configuration of the frequencies for which we want to calculate the bounds for the specifications currently selected. For the example proposed, the type 1 specification must consider all the frequencies (14), whilst specification type 6 considers, for example, the set of frequencies $\{0.1, 0.5, 1, 15\}$.

The $W(s)$: Zeros Poles zone displays a map of

poles and zeroes that allows a configuration by means changing the value with the mouse of the transfer function $W(s)$ associated to a certain specification. It is possible to add, move and suppress the zeros and the poles of $W(s)$. As the transfer function $W(s)$ associated to the specification is configured, it is possible to view simultaneously and interactively in the window how the modulus changes in the Bode diagram and how the bounds associated to the aforementioned specification also changes in the Nichols diagram. For the proposed example, it would be necessary to configure the transfer functions associated to the type 6 specifications in this specific zone. In the case of W_{s6a} it would be necessary to configure a simple zero in -30 , a pair of natural frequency conjugated complex poles $\omega_0 = 4.44$ (rad/s) and dampening factor $\delta = 0.45$. On the other hand, for the case of W_{s6b} it would be necessary to configure three simple poles in -3 , -4 and -10 . The gains of the transfer functions would be configured in the $W(s)$ frequency-domain specification zone

The modulus of the specification $W(s)$ selected is represented in a Bode magnitude diagram in the $W(s)$: Magnitude specification zone. The contents of this graph are updated simultaneously and interactively when the gain, zeros and poles of the specification $W(s)$ change. For the proposed example, Fig. 5 shows in this zone $W_{s6a}(s)$ and $W_{s6b}(s)$. Also shown the trial frequencies for $W_{s6a}(s)$ (triangles) and for $W_{s6b}(s)$ (circles).

The Nichols Plot zone displays the bounds associated to the selected specification, the entire set of bounds of the active specifications or the

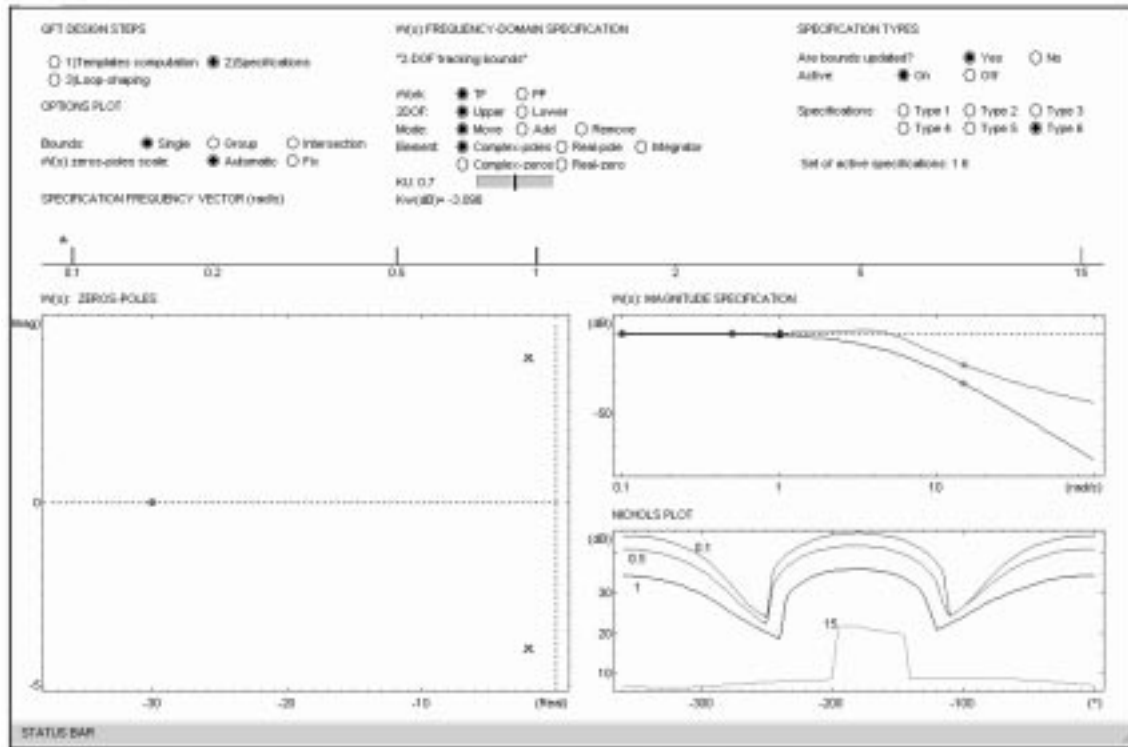


Fig. 5. Stage 2 Specifications of the proposed example

intersection of the bounds. Figure 5 shows in this zone how the Nichols diagram represents the bounds associated to the type 6 specification once configuration has taken place.

Stage 3: Loop-shaping. The display of the tool corresponding to the *loop-shaping* stage shows (see Fig. 6) two new zones: Operations over controller C and $C(s)$: zeros -poles. In the first zone the user can select the type of item (gain, real-pole, real-zero, complex-pole or complex-zero) associated with the controller $C(s)$ subject to input or manipulation in the zones $C(s)$: Zeros-Poles and Nichols Plot. Also available is a slider by means of which it is possible to configure the value of the gain of the controller.

In the $C(s)$: Zeros-Poles zone it is possible to modify by dragging the object that represent the zeroes (o) and poles (x) of the controller $C(s)$. It is also possible to view the zeroes and poles of the nominal plant. The actions carried out in this zone are reflected immediately in an interactive way in the representation of the nominal open loop transfer function $L_0(j\omega)$ in the Nichols diagram as well as the symbolic representation of the transfer function $C(s)$.

During the design stage and in the Nichols Plot, further to the graphical representation of the final bounds $B(\omega_i)\omega_i \in \Omega$ associated to the specifications the function $L_0(j\omega)$ is also represented. The main manipulation that the user can perform within this area of the programme is the displacement of $L_0(j\omega)$ in certain directions in the Nichols

diagram depending on the selected controller item in the Operations Over Controller C zone.

The changes made to $L_0(j\omega)$ 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 which appears under the Nichols Plot zone. 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. For the proposed example, Fig. 6 displays the aspect of the QFTIT window after finishing the Loop-Shaping stage. The Nichols diagram shows the bounds $B(\omega_i)\omega_i \in \Omega$ and the designed $L_0(j\omega)$. It can be observed how each point $L_0(j\omega_i)$ (circle) fulfil the boundary $B(\omega_i)$. The expression of the designed controller is

$$C(s) = \frac{604541.66 \cdot (s + 5)}{s^2 + 2 \cdot 0.6 \cdot 253.1 \cdot s + (253.1)^2} \quad (15)$$

This is a controller with a simple zero and a pair of conjugate complex poles which are represented in the $C(s)$: Zeros-Poles zone.

Stage 4: Pre-filter design. The zones of this stage and their interaction are very similar to the previous stage. Instead of the Nichols plot zone appears Pre-filter Shaping. In this zone the maximum and minimum values of the closed loop transfer function $F(s) \cdot [L(s)/(1 + L(s))]$ and the

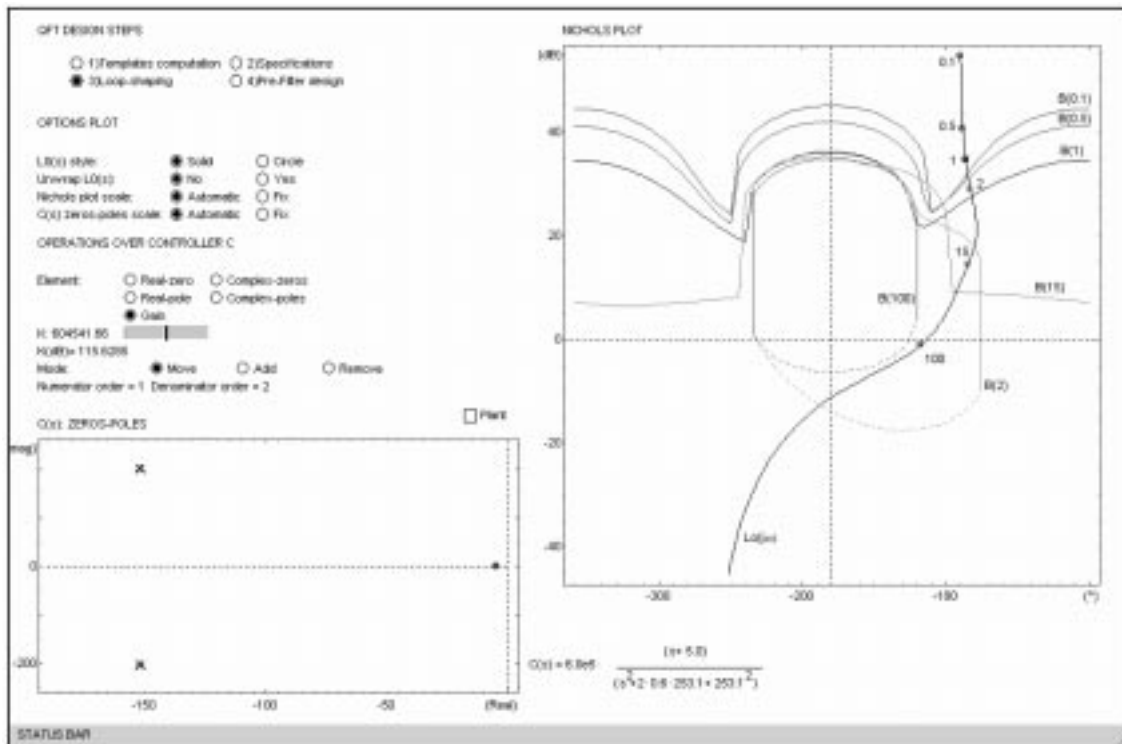


Fig. 6. Stage 3 Loop-shaping of the proposed example

specifications $W_{6a}(s)$ and $W_{6b}(s)$ are represented in a Bode magnitude diagram. The main manipulation that the user can perform within this area of the programme is the displacement of the maximum and minimum values of $F(s) \cdot [L(s)/(1 + L(s))]$ in certain directions in the Nichols diagram depending on the selected $F(s)$ item. Figure 7 shows the Pre-filter shaping zone at the end of stage 4 for the proposed example. The display shows how the pre-filter

$$F(s) = \frac{0.25 \cdot (s + 78.0)}{s^2 + 2 \cdot 0.7 \cdot 4.4 \cdot s + (4.4)^2} \quad (16)$$

made up of a single zero and a conjugate complex pole has been able to adjust the maximum and minimum values of the closed loop transfer function $F(s) \cdot [L(s)/(1 + L(s))]$ within the defined specifications in (13).

Stage 5: Validation. The display of the tool corresponding to the *Validation* stage shows (see Fig. 8) four new zones: Selection of the specification to validate, Validation, Manipulated variable and Controlled variable. It is also possible to show another additional zone: System: Zeros-Poles.

In the Selection of the specification to validate zone the user can select the chosen specification to be validated. The Validation zone displays Bode magnitude diagram, which includes, depending on the selected Type i specification, the modulus of its $W_i(s)$ and the worst case modulus of the characteristic function of the system (see Table 2) which is to be validated. For the proposed example, Fig. 8 displays a horizontal line situated at 1.6 dB which

is the representation of the robust stability specification $W_{s1} = 1.2$. Also displayed is the maximum value of the closed loop transfer function without considering the pre-filter $\max|L(j\omega)/(1 + L(j\omega))|$. 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 stage 3. With respect to the other specification established for this example. If the Type 6 specification is selected for validation, the same figure that appears in stage 4 in the Pre-Filter shaping (see Fig. 7) appears now in the *Validation* zone, showing that with the designed pre-filter, the specification is fulfilled.

The Manipulated Variable and Controlled variable zones show the manipulated variable $u(t)$ and the controlled variable $y(t)$, respectively. It is possible to view the values of these variables for the case of the non-compensated closed loop system ($F = 1, C = 1$) and/or for the case of a compensated closed loop system. For the proposed example, Fig. 8 above shows the outputs of $u(t)$ and $y(t)$. Also displayed are the upper level and the lower since the Type 6 specification was established in the controlled variable figure. The user's option regarding manipulation in this zone consists on the configuration of a manipulated variable regarding the instant and the magnitude of a step type perturbation. This figure as well as the controlled variable figure show simultaneously how this perturbation affects these variables.

The System: Zeros-Poles zone allows the display of a complex plane with the zeroes and poles of the plant (including uncertainties), the controller, the pre-filter and the closed loop system. It is possible

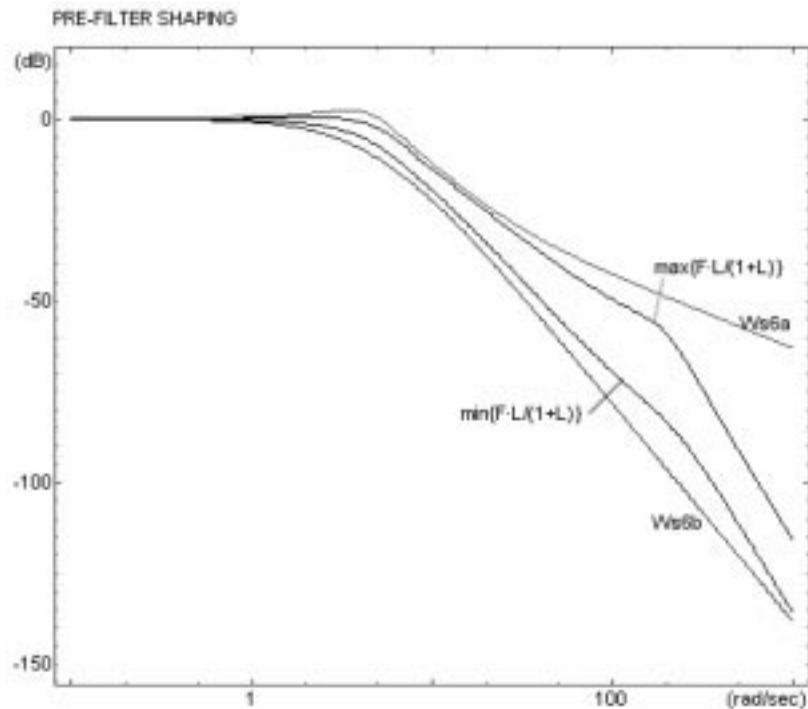


Fig. 7. Pre-filter Shaping zone of the proposed example

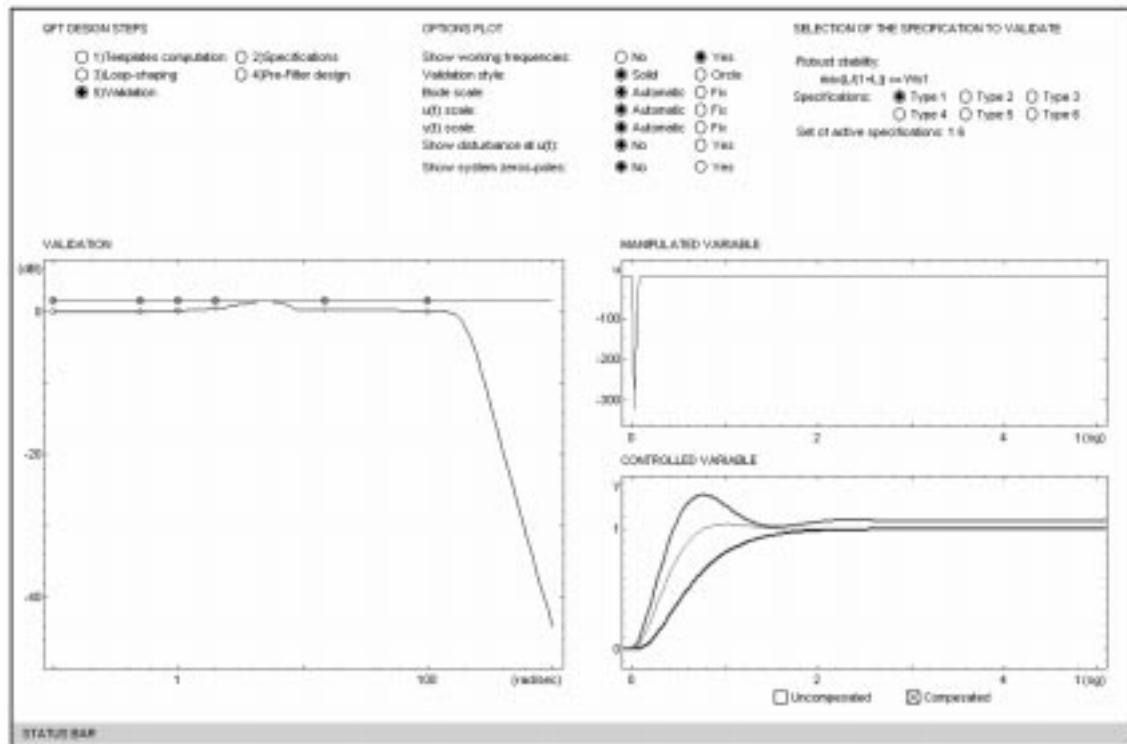


Fig. 8. Stage 5 Validation of the proposed example

to manipulated the nominal value of the plant's zeroes and poles. Simultaneously and interactively the display of the manipulated and controlled variables would be updated.

Settings menu

The QFTIT tool has a Settings menu that includes a total of thirty entries divided into nine groups. When the user selects any of these entries a dialogue box is displayed which includes a number of blank fields to be completed. By doing so it is possible to perform the majority of the actions that could be performed by using the mouse as well as other additional functions, for example, data input/output operations with the tool.

EDUCATIONAL APPLICATIONS OF QFTIT

QFTIT can be used with practical purposes to solve robust control problems, or with educational purposes to teach the QFT methodology. From an educational point of view, the ease of use and interactive nature of QFTIT are very useful for professors and students.

Professors can use QFTIT to illustrate their in-class QFT methodology explanations, and to make laboratory work or homework for the students.

The QFTIT layout quickly teaches the students that the QFT methodology consist of several stages (Templates computation, Specifications, Loop-shaping, Pre-filter design, and Validation). These stages have to be completed in sequence (at least in a first iteration) to arrive at the goal: the

successful design of a robust controller which fulfils specifications.

In the Template computation stage (see Fig. 3 above) students can learn the influence of the uncertainty magnitude and the kind of plant element (gain, zero or pole) in the size and shape of a template. If students select a kind of plant element in The Operations over plant P zone and increase or decrease its uncertainty in the Uncertainty Plant Description zone, they can visualise how the templates change in the Templates zone.

Likewise, in this same stage, students can learn that the template shape also depends on the frequency. At very low or very high frequencies the template shape is approximately a vertical segment. This property can be used to establish the limits of the set of trial frequencies Ω . Students can visualise this template property in the Template zone. They only have to select a vertical segment associated with a certain frequency segment in the Template frequency vector zone, and drag it left (decrease frequency) or right (increase frequency) till the template shape is a vertical segment.

In the Specifications stage (see Fig. 5 above) students can learn how the shape of a bound depends on the frequency and the specification gain. Students can visualise this property in the Nichols plot zone if they drag the Kw slider in the $W(s)$ frequency-domain specifications zone. The Nichols Plot zone shows the bounds associated to the specifications in different colours. Each colour is associated with a certain frequency. This feature helps students to distinguish the bounds.

Table 2. Specifications implemented in QFTIT

Type	Specification
1: Robust stability	$\left \frac{P}{1+P} \right \leq W_{s1}$
2: Disturbances rejection at plant output	$\left \frac{1}{1+P} \right \leq W_{s2}$
3: Disturbances rejection at plant input	$\left \frac{P}{1+P} \right \leq W_{s3}$
4: Control effort	$\left \frac{C}{1+P} \right \leq W_{s4}$
5: Tracking bandwidth	$\left \frac{P}{1+P} \right \leq W_{s5}$
6: 2-DOF tracking	$W_{s6a} \leq \left(\left \frac{P}{1+P} \right \right) \leq W_{s6b}$

Another idea that students can learn in this stage is that certain specifications can not be simultaneously fulfil. If the Intersection option in the Options plot zone is selected then the Nichols Plot zone shows the intersection of all the bounds associated to each established specification. If an intersection cannot be done at a certain frequency then QFTIT shows a message in the window to warn that it is not possible to simultaneously fulfil all the specification. In this case, some of the specifications must be relaxed or eliminated.

In the Loop-shaping stage (see Fig. 6 above) students can quickly learn how a controller element (gain, simple zero, simple pole, complex zeroes or complex poles) modifies the open-loop transfer function $L_0(s)$ in the Nichols chart. Students only have to select a kind of element and the Add operation in the Operations over controller C zone, place the mouse over L_0 , and drag it. The L_0 shape is instantaneously modified if the dragging is feasible with that kind of element. The QFTIT interactivity in this stage helps students to gain skill in the synthesis of the controller G .

Besides, QFTIT interactivity also allows students to learn in the Pre-filter shaping stage how a pre-filter element modifies the closed-loop transfer function T .

In the Validation stage (see Fig. 8), students can determinate the frequencies where a specification is not fulfilled. They only have to place the mouse over the characteristic function of the system (see Table 2) which is validated at the frequency where this fact occurs. The value of the frequency is displayed in the Status bar.

Likewise, students can learn an important idea in this stage: the fulfilment of the specifications in the frequency domain does not guarantee its fulfilment in the time domain. They only have to look at the Validation and Controlled variable zones.

CONCLUSIONS

This paper has described the present version of the QFTIT software tool for the design of robust controllers using the QFT methodology. QFTIT has been developed using SYSQUAKE. It is freely available as an executable file for Windows platforms at <http://ctb.dia.uned.es/asig/qftit/>

The main contributions of QFTIT compared to other existing tools are its ease of use and greater interaction. In QFTIT the user only has to operate with the mouse over the different types of items which appear in the tool's display or, if preferred, fill-in the blank fields of the dialogue boxes. Any action performed by the user will be displayed immediately in all the graphs displayed. Thus, the user is aware of the effects of his/her actions during the design development.

QFTIT can be used to solve robust control problems, or with educational purposes to teach the QFT methodology. From an educational point of view, the ease of use and interactive nature of QFTIT are very practical for professors and students.

Future QFTIT releases will include other types of plant definition, other templates calculation algorithms and multivalued bound consideration. Further to this, the MIMO-QFTIT tool will be implemented for reduced order multivariable systems.

The authors welcome any suggestions or comments from QFT advanced designers, professors or students to improve the tool.

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