INTERACTIVE EDUCATIONAL ENVIRONMENT FOR DESIGN BY QFT METHODOLOGY

S. Dormido, J. Aranda, J.M. Díaz, S. Dormido Canto

Dpt. de Informática y Automática. Fac. Ciencias. UNED. Madrid. Spain
Fax: 34 91 398 66 97. Phone : 34 91 398 71 48. E -mail : jaranda@ dia.uned.es

Abstract: For students that begin the learning in control engineering many concepts are not very intuitive at first, due their properties are expressed in two different domains: the time and the frequency domains. Transient behavior, such as settling time, overshoot and the risk of saturation is analyzed typically in the time domain; while concepts like stability, noise rejection and robustness are expressed more easily in the frequency domain. In loop shaping on Nichols chart, the designer must to have enough skill to add necessary elements (gain, poles and zeros) to the controller until the nominal loop lies near its bound. This aspect of the QFT design is usually the most difficult for students. This paper discusses an interactive environment in Sysquake for the design by QFT methodology, where the student can be see immediate the effect of modifying the parameters.

Keywords : Educational aids, QFT, Interactive, Loop shaping

1. INTRODUCCION

To design technical systems or simply to understand the physical laws that describe their behavior, scientists and engineers often use computers to calculate and represent graphically different magnitudes. In control engineering, these quantities include among others: time and frequency responses, poles and zeros in the complex plane, Bode, Nyquist and Nichols diagrams, phase plane, etc. Frequently, these magnitudes are closed related; they constitute different visions of the same reality. The understanding of these relationships is one of the keys to achieve a good learning of the basic concepts and allows to the student to be in disposition of carrying out control systems designs with sound sense.

Traditionally, the design of the systems is carried out following an iterative process. Specifications of the problem do not usually use directly to calculate the value of the parameters of the system because there is not an explicit formula that relates them directly. This is the reason of dividing each iteration in two phases. The first one, often called synthesis consists on calculating the unknown parameters of the system based on a group of design variables (that are related with the specifications). 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 again.

It is possible however to merge both phases into one where the effect of modifying the parameters produces an immediate effect. In this way the design procedure becomes really dynamic and the student perceives the gradient of the change of the performance criteria with regard to the elements that manipulates. This interactive capacity allows to identify much more easily the compromises that can be achieved.

At the present time a new generation of software packages have allowed to arise an interesting alternative for the interactive learning of the automatic control. These tools are based on objects that admit a direct graphic manipulation. During these manipulations, the objects are updated immediately, so that the relationships among the objects is maintained in all moment. Ictools and CCSdemo, developed in the Department of Automatic Control at Lund Institute of Technology and Sysquake (Piguet, 1999) in the Institut

d'Automátique of the Federal Polytechnic School of Lausanne are good examples of this new educational philosophy of teaching automatic control. For those that begin the learning in this field many concepts are not very intuitive at first, due their properties are expressed in two different domains: the time and the frequency domains. Transient behavior, such as settling time, overshoot and the risk of saturation is analyzed typically in the time domain; while concepts like stability, noise rejection and robustness are expressed more easily in the frequency domain. The basic mechanisms that relate them and other phenomenon like for example the effects of the sampling and the non linear elements to mention some few can be illustrated in a very effective way using these tools.

Taking into account this philosophy this paper discusses an interactive environment in Sysquake for the design by QFT methodology, where the student can see immediately the effect of modifying the parameters. Several graphics are displayed simultaneously, and some elements can be manipulated with the mouse. During the manipulation, all the graphics are updated in a coherent way to reflect the change.

This aplication is used in the design of an academic example and in the design of a controller for a real plant.

2. INTERACTIVITY IN DESIGN BY QUANTITATIVE FEEDBACK THEORY

Figure 1 shows a general diagram for a feedback control system. Where F is the pre-filter, G is the controller, P is the plant and H is the sensor. R is the reference signal and Y is the output. It can be subjected to reference disturbances W, input plant disturbances V and output plant disturbances D. Besides the sensor has a noise N.
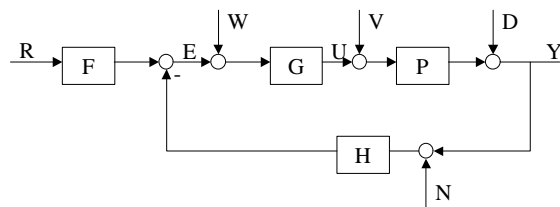

Fig. 1. Feedback Control System

The main goal is to design a robust controller that considers parametric uncertainty of the plant P. The design must to carry out several performance specifications: Tracking of a reference R, control effort limits and disturbances rejection.

To shape the loop gain in order to obtain desired specifications is really at the heart of what is now called "classical methods". Bode, Nichols and many other control practioners developed graphical methods and special diagrams to obtain this in a simple way for siso systems.

The basic elements for directly manipulating the loop gain are the well known pure gain, lead and lag compensation.

QFT introduced by Horowitz (1963) was developed with the same philosophy in mind. The goal of QFT is to ascertain in an explicit way that the loop gain specifications are verified (mantained) under given model uncertainty.

The basic principle is to describe the controller system by a set of transfer functions which at each frequency defines a set in a Nichols chart. This sets, in the QFT terminology, are called templates.

The requirement is that, at each frequency, the specifications for the closed loop system must be fullfilled for all elements in the template.

The consequence is to impose some constraints in the controller's frequency response which can be related in a simple way to contraints in the nominal loop gain.

This mechanism transforms the design procedure from a simultaneous and very difficult synthesis problem to a classical control problem with one nominal process model with constraints.

Using Quantitative Feedback Theory is able to design a robust controller. This technique looks for a design that combines:
- Obtaining the performance specifications.
- Plant variations inside uncertainty regions (Robustness).

QFT methodology has several stages:
- Synthesis of tracking models.
- Modelling disturbances
- Obtaining plant templates.
- Choosing the nominal plant.
- Generating stability bounds.
- Generating performance bounds.
- Intersection of all bounds.
- Loop shaping (Synthesis of controller G_c).
- Pre-Filter shaping
- Analysis, simulation and validation.

Obtaining plant templates and generating of different bounds usually needs a demanding

computational work. In this stages the designer must to program algorithms and waiting for results.

In the loop shaping phase on Nichols chart, the designer must to have enough skill to add necessary elements (gain, poles and zeros) to the controller G_c until the nominal loop satisfies the specifications and results in closed-loop stability.

This aspect of the QFT design is usually the most difficult for novice designers. For them, it is sometimes easier to design a controller Gc using root locus plot, Bode plot or step response plot.

The interactive design environment in Sysquake for loop shaping (IDESQLS) shows in a same window: Nichols chart, Bode plot of open-loop transfer function, root locus plot and step response plot of closed-loop transfer function.

Therefore designer counts in IDESQLS with other well-known figures to verify the results of modifications that he inserts into nominal open-loop in Nichols chart.

3. DESCRIPTION OF THE INTERACTIVE DESIGN ENVIRONMENT

Sysquake (Piguet, 1999) is an interactive design CAD tool for automatic control and signal processing. It was developed in the Institut d'Automátique of the Federal Polytechnic School of Lausanne.

Sysquake's window can simultaneously display several interactive figures. So IDESQLS shows in a same window: Nichols chart, Bode and root locus diagrams and the step response plot of the closed-loop transfer function. User can select the figures that he wants to see in a window and to modify the size of all the figures.

Sysquake allows to the user to interact some elements of its figures with the mouse. During the manipulation, all the graphics are updated in a coherent way in order to reflect the change. In IDESQLS, the user can select the element (gain, pole or zero) that he wants to add to the controller G, to place the mouse over nominal open-loop on Nichols chart and to drag it in order to set the value of the added element. The introduced modifications in the Nichols chart are displayed simultaneously in the other figures.

Sysquake has a setting menu where the user can set the value of different parameters of the displayed figures. In IDESQLS user can define the transfer function of the controller G and the type of element that will be added to the present controller as he drags the nominal open-loop in Nichols chart. Also IDESQLS allows to the user to select a data file to draw stability bounds and performance bounds in Nichols chart.

Sysquake displays different information in a messages bar as the user places the mouse over the different elements of the figures. For example, in IDESQLS as the mouse is placed over a bound, the bound generation frequency is displayed in the messages bar. Whereas if the mouse is placed over a point of nominal open-loop plot, frequency, magnitude and phase are displayed in the messages bar.

4. EXAMPLES

4.1 A classic example of loop shaping.

In this section a classic example (Borghesani et al, 1995) of loop shaping is done using IDESQLS.

Let the uncertain plant, P(s), described by the following parametric family $\vec{P}$

$$\vec{P} = \left\{ P(s) = \frac{k}{(s+a)(s+b)} : k \in [1,10], a \in [1,5], b \in [20,30] \right\}$$

The feedback problem is to design a controller, G(s), such that the closed-loop system verifies the following specifications:
1) Robust stability with at least 50° phase margin for all P(s) $\in \vec{P}$.

$$\left| \frac{P(jw)G_C(jw)}{1+P(jw)G_C(jw)} \right| \leq 1.2, \; for\,all\,P \in \vec{P}, w \in [0, \infty)$$

2) Reject plant output disturbance according to:

$$\left| \frac{Y(jw)}{D(jw)} \right| \leq \left| 0.02 \frac{(jw)^3 + 64(jw)^2 + 748(jw) + 2400}{(jw)^2 + 14.4(jw) + 169} \right|,$$
$$for\,all\,P \in \vec{P}, w \in [0,10]$$

3) Reject plant input disturbance according to:

$$\left| \frac{Y(jw)}{D(jw)} \right| \leq 0.01, \; for\,all\,P \in \vec{P}, w \in [0,50]$$

Templates, stability bounds and performance bounds has been calculated in the following frequencies:
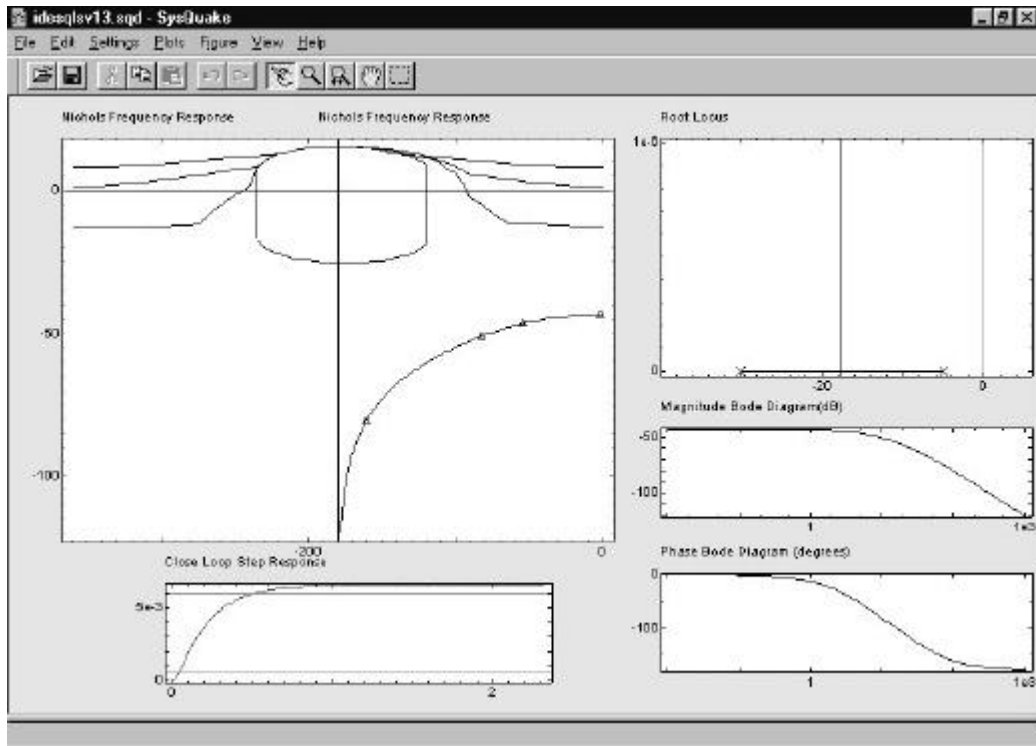
$$w = [0.1, 5, 10, 100] \; (rad/seg)$$

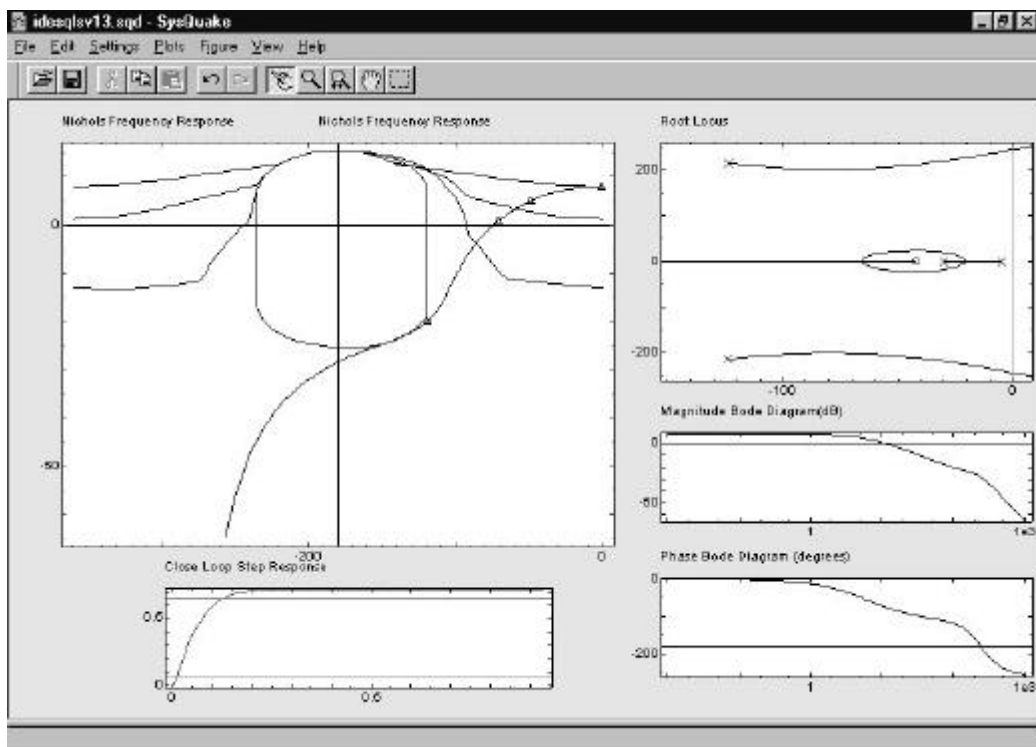Fig 2. Window of IDESQLS in the beginning of the example.

Fig 3. Window of IDESQLS in the end of the example.

The nominal plant is:

$$P_0 = \frac{1}{s^2 + 35s + 150}$$

Initially, the controller G is a simple unit gain. Figure 2 shows the window of IDESQLS for this example. To verify the performance bound at ω=0.1 rad/seg is necessary to increase the gain of the controller. The type of block *'Gain'* is default selected in the Settings menu. The evaluated nominal open-loop at the frequency ω is represented by a triangle in the Nichols chart. The user must to drag up the nominal open-loop plot till the first triangle on the right-hand side is over the upper bound.

User can observe that a phase lead is necessary because the nominal loop lies inside the stability bounds at frequencies higher than ω=100 rad/seg. It is neccesary to add a real zero. So, selecting *Real Zero* in the Settings menu, the user must to place the mouse at ω=60 rad/seg and to drag the nominal loop till obtaining z=42.

Finally the controller design involves shaping the high frequency response of the nominal loop with the goal objetive of dropping its magnitude as fast as possible. A strictly proper controller is obtained adding a pair of complex poles. So, selecting *Complex Pole* in the Settings menu, the user must to place the mouse over the nominal loop and to drag the nominal loop till obtaining δ=0.5 y ω_n=248. The final controller is

$$G = \frac{380\left(1 + \dfrac{s}{42}\right)}{\left(\dfrac{s^2}{248^2} + \dfrac{s}{248} + 1\right)}$$

The introduced modifications in the Nichols chart has been reflecting inmediately over the remaining figures of the window (see Figure 3).

4.2 A real example of loop shaping.

The main problem for the development of high speed craft is concerned with the passenger's comfort and the safety of the vehicles. The vertical acceleration associated with roll, pitch and heave is the main cause of motion sickness. The roll control is the most attractive candidate for control since increasing damping can be obtained more easily. However, shipbuilders are also interested in increasing pitch and heave damping. In order to solve the problem antipitching devices and pitch

control methods must be considered. Previously, models for the vertical ship dynamics must be developed for the design, evaluation and verification of the results.

Once the modelling stage of vertical dynamics of a high speed ferry (De la Cruz, et al., 1998; Aranda, et al., 2000) and actuators (Esteban, et al., 2000) is completed then the next stage is to design a controller on heave and pitch motions in order to command the positions of the actuators. The final goal is to decrease the vertical accelerations to reduce motion sickness.

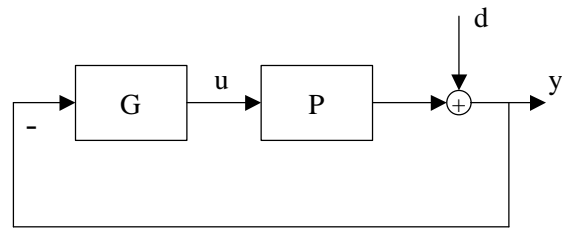The feedback system under consideration is schematically described in Figure 4.

Fig. 4. Feedback system under considerations

The model of the plant P is the model of vertical dynamic of a high speed ferry properly conected to the model of the actuators. The input plant u is the position of the actuator (T- Foil) and the output plant y is the pitch motion that it is subjected to one perturbation: wave height (d).

P is an uncertain plant, described by the parametric family $\vec{P}$:

$$\vec{P} = \left\{ \begin{array}{l} P(s) = K\dfrac{(s+a)(s+b)}{(s+100)(s+1.8)(s+0.4915)(s^2+cs+d)}; \\ K = [-0.87, -0.34], a = [-7.85, -5.79], b = [0.016, 0.041], \\ c = [0.86, 1.16], d = [2.27, 2.80] \end{array} \right\}$$

The feedback problem is to design a controller, G(s), such that the closed-loop system verifies the following specifications:

1) Robust stability with at least 50° phase margin for all P(s) $\in$ $\vec{P}$.

$$\left| \frac{P(jw)G_C(jw)}{1+P(jw)G_C(jw)} \right| \leq 1.2, \ for\,all\,P \in \vec{P}, \, w \in [0, \infty)$$

2) Plant output disturbance rejection (sensitivity) for any P$\in$ $\vec{P}$, $\omega\in$ [0.5, 2]. The transfer function from the disturbance at the plant output to the plant output is bounded by:
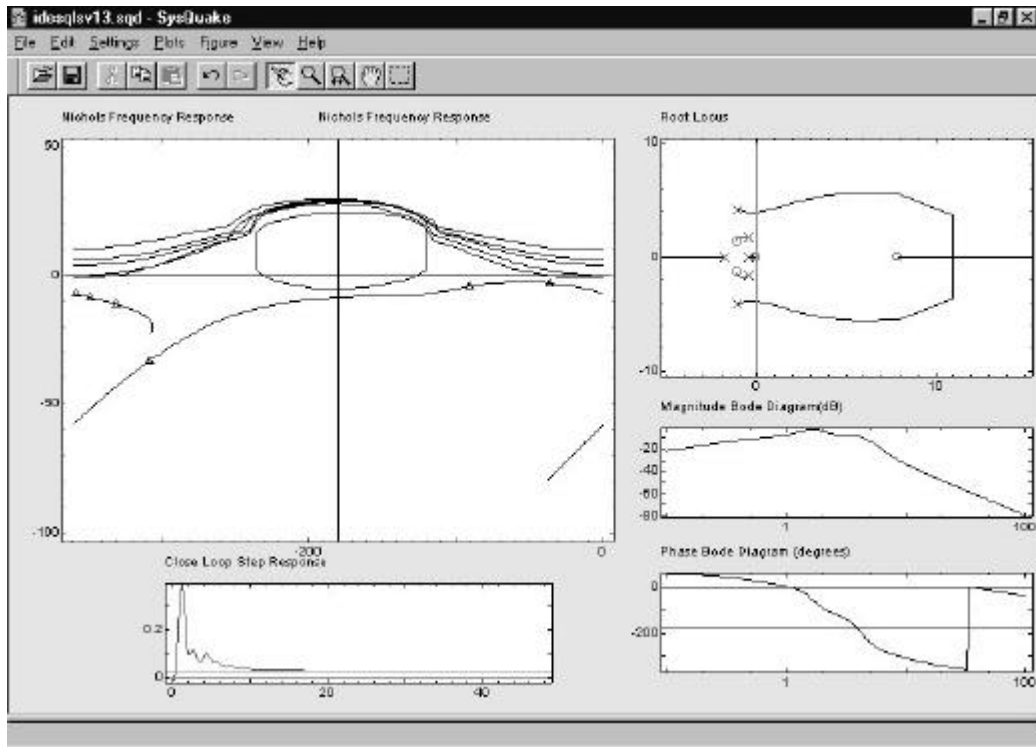
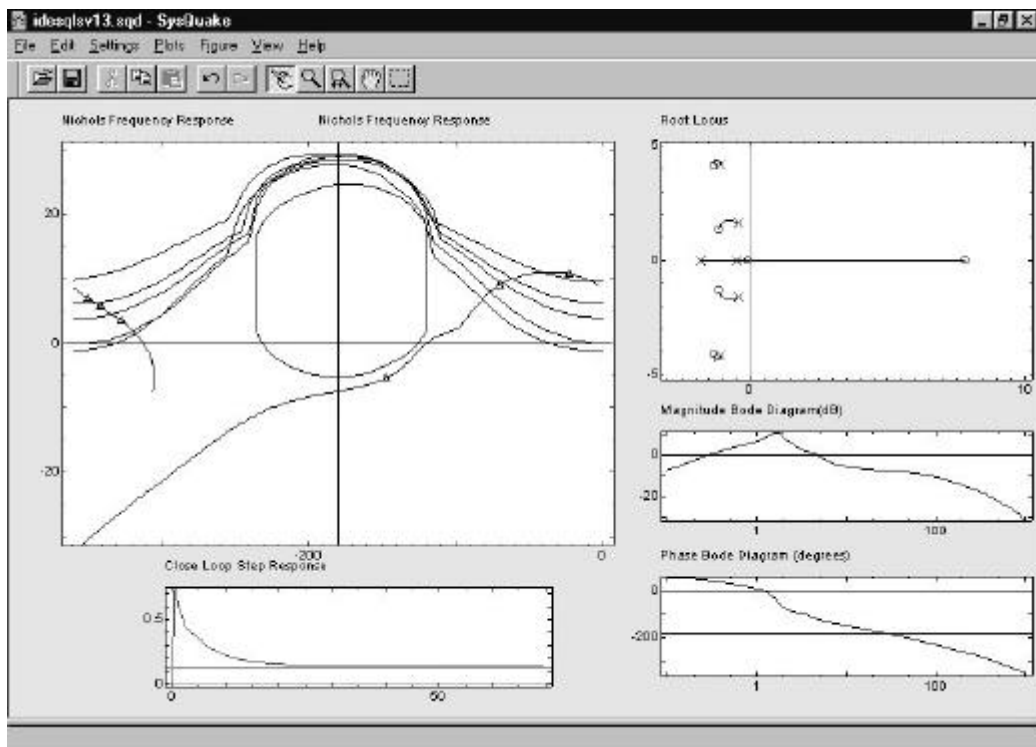Fig.5. Window of IDESQLS in the beginning of the example.

Fig. 6. Window of IDESQLS in the end of the example.

$$\left|\frac{Y(jw)}{D(jw)}\right| \leq \left|\frac{1.15(jw)^4 + 3.626(jw)^3 + 6.515(jw)^2 + 8.273(jw) + 2.856}{(jw)^4 + 3.96(jw)^3 + 7.793(jw)^2 + 10.43(jw) + 2.914}\right|$$

Templates, stability bounds and performance bounds has been computed at the frequencies

$$w = [0.5, \ 0.8, \ 1, 1.5, 2, 10] \ \ (rad \, / \, seg)$$

The nominal plant is:

$$P_0 = \frac{-0.87s^2 + 6.798s + 0.2855}{s^5 + 107s^4 + 333.1s^3 + 595.7s^2 + 749.7s + 257.9}$$

A classical controller was designed for this plant. The controller G_0 is a second order filter that it was tuned for the nominal plant solving a non linear optimization problem .

$$G_0 = \frac{170.3s^2 + 385.6s + 518.7}{s^2 + 2.172s + 18.47}$$

Figure 5 shows the window of IDESQLS for this loop shaping problem when $G=G_0$.

G_0 is a good controller for the nominal plant, but the previous specification of plant output disturbance rejection is not verified.

To satisfy the performance bounds is necessary to increase the gain controller. The user must to drag up the nominal open-loop plot till the first triangle on the right-hand side is over the upper bound. It can be observed that a phase lead is necessary because the nominal loop lies inside the stability bounds. It is neccesary to add a pair of complex zeros, the user must to drag the nominal loop till obtaining a natural frequency ω_n=4.32 rad/seg and a damping factor δ=0.31. The final step to design the controller involves shaping the high frequency response of the nominal loop with the goal of dropping its magnitude as fast as possible. User must place the mouse over the nominal loop and to drag the nominal loop till obtaining δ=0.8 y ω_n=1000. The final controller is

$$G_C = \frac{1.67 \cdot 10^5 \left(\dfrac{s^2}{1.74^2} + \dfrac{2 \cdot 0.65 \cdot s}{1.74} + 1\right)\left(\dfrac{s^2}{4.32^2} + \dfrac{2 \cdot 0.31 \cdot s}{4.32} + 1\right)}{\left(\dfrac{s^2}{4.3^2} + \dfrac{2 \cdot 0.25 \cdot s}{4.3} + 1\right)\left(\dfrac{s^2}{1000^2} + \dfrac{2 \cdot 0.8 \cdot s}{1000} + 1\right)}$$

These modifications over the Nichols frequency response has been reflecting over the remaining figures of the window (see Figure 6). We can see that all specifications are satisfied.

5. CONCLUSION

An interactive design environment for loop shaping was built in Sysquake. This application get that ours students understand faster and best the synthesis of controllers   using the QFT methodology. They counts in IDESQLS with other well-known figures to verify the results of modifications that insert into nominal open-loop in Nichols chart, so the design and analysis phases are merged into one, and the student can be see immediate the effect of modifying the parameters.

This paper shows as IDESQLS is used in an academic example, appropriate   for teaching. Also IDESQLS is used in the design of controller for a practical problem. This design is compared with a previously classical controller.

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