

INTERACTIVE EDUCATIONAL ENVIRONMENT FOR DESIGN BY QFT METHODOLOGY

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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. INTRODUCTION

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 closely 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 the student to carry out control systems designs with sound sense.

Traditionally, the design of the systems is carried out following an iterative process. Specifications of the problem are not normally directly used to calculate the value of the system parameters because there is not an explicit formula that relates them directly. This is the reason for dividing each iteration into two phases. The first one, often called synthesis consists on calculating the unknown parameters of the system. These parameters are 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 result of modifying the parameters produces an immediate effect. In this way the design procedure becomes really dynamic and the student feels 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 the arising of 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 immediately are updated, so that the relationship among the objects is maintained at all moments. Ictools and CCSdemo, developed in the Department of Automatic Control at Lund Institute of Technology and Sysquake (Piguet, 1999) and in the Institut d'Automatique of the Federal Polytechnic School of Lausanne are good examples

of this new educational philosophy for teaching automatic control. For those that begin the learning in this field many concepts are not very intuitive at first, due to the fact that 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 are 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 phenomena as for example the effects of the sampling and the non-linear elements, to mention just a 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 using 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 changes.

This application 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 USING 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 .

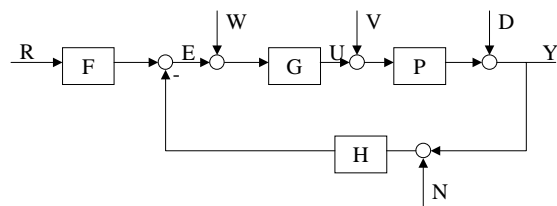


Fig. 1. Feedback Control System

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

The shaping of the loop gain in order to obtain the desired specifications is really at the heart of what is

now called “classical methods”. Bode, Nichols and many other control practitioners developed graphical methods and special diagrams to obtain this in a simple way for siso systems. The basic elements for manipulating the loop gain directly are the well known pure gain, lead and lag compensation.

QFT introduced by Horowitz (1963, 1972) 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 maintained under the given model uncertainty.

The basic principle is to describe the controller system by a set of transfer functions which define a set in a Nichols chart at each frequency. These sets are called templates in the QFT terminology. The requirement is that, at each frequency, the specifications for the closed loop system must be fulfilled for all elements in the template.

The aim is to impose some constraints in the controller’s frequency response which can be related in a simple way to the restrictions in the nominal loop gain. This mechanism transforms the design procedure from a simultaneous and very difficult synthesis problem into a classical control problem with one nominal process model with constraints.

By using Quantitative Feedback Theory a robust controller can be designed. This technique looks for a design that combines the following requirements:

- 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).
- Pre-Filter shaping
- Analysis, simulation and validation.

Obtaining plant templates and generating different bounds usually needs a demanding computational work. In this stages the designer must program algorithms and wait for results.

In the loop shaping phase on Nichols chart, the designer must have enough skill to add necessary elements (gain, poles and zeros) to the controller G

until the nominal loop satisfies the specifications and results in closed-loop stability.

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

The interactive design environment in Sysquake for loop shaping (IDESQLS) shows the following in an only window: Nichols chart, Bode and root locus diagrams and the step response plot of the closed-loop transfer function.

Therefore IDESQLS provides the designer with other well-know tools for analysis in order 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'Automatique of the Federal Polytechnic School of Lausanne.

Sysquake's window can simultaneously display several interactive figures. So IDESQLS shows the following in an only window: Nichols chart, Bode and root locus diagrams and the step response plot of the closed-loop transfer function. The user can select the figures that he wants to display and it is possible to resize all the figures.

Sysquake allows the user to interact some elements of its figures by using the mouse. During the manipulation, all the graphics are updated in a coherent way in order to reflect the changes. The user can select the element (gain, pole or zero) that he wants to add to the controller G , in order to place the mouse over nominal open-loop on Nichols chart and drag it in order to set the value of the added element. The modifications introduced 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 the user can define the transfer function of the controller G and the type of element that will be added to the present controller when he drags the nominal open-loop in Nichols chart. IDESQLS also allows the user to select a data file to draw stability 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 the 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 $P(s) \in \vec{P}$.

$$\left| \frac{P(j\omega)G_c(j\omega)}{1+P(j\omega)G_c(j\omega)} \right| \leq 1.2, \text{ for all } P \in \vec{P}, \omega \in [0, \infty)$$

2) Reject plant output disturbance according to:

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

3) Reject plant input disturbance according to:

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

Templates and stability and performance bounds have been calculated in the following frequencies:

$$\omega = [0.1, 5, 10, 100] \text{ (rad / seg)}$$

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 IDESQLS window for this example. To carry out the performance bound at $\omega=0.1$ rad/seg it is necessary to increase the gain of the controller.

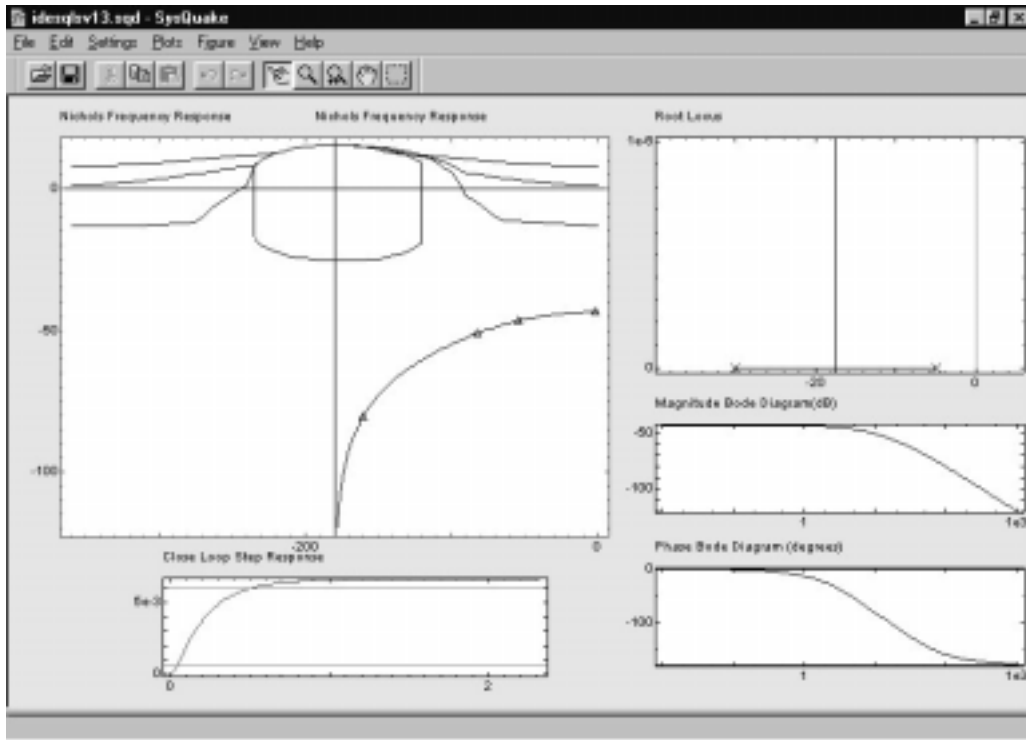


Fig 2. Window of IDESQL in the beginning of the example.

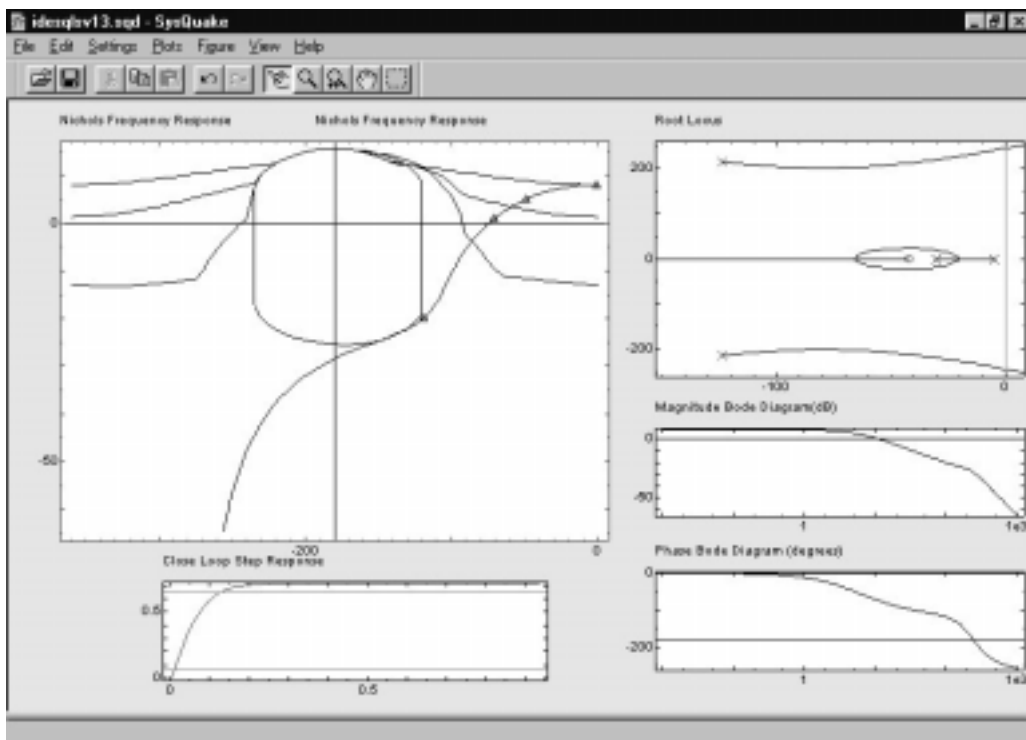


Fig 3. Window of IDESQL in the end of the example.

The type of block 'Gain' is selected by default in the Settings menu. The evaluated nominal open-loop at the frequency ω is represented by a triangle in Nichols chart. The user must drag up the nominal open-loop plot till the first triangle on the right-hand side is over the upper bound.

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

Finally the controller design involves shaping the high frequency response of the nominal loop with the objective that its magnitude falls as fast as possible. A strictly proper controller is obtained by adding a pair of complex poles. So, by selecting *Complex Pole* in the Settings menu, the user must place the mouse over the nominal loop and drag the nominal loop till obtaining $\delta=0.5$ y $\omega_n=248$. The final controller is

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

The modifications introduced in Nichols chart are immediately updated in 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 damping can be increased 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 design, evaluation and verification of the results.

Once the modelling phase of the 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.

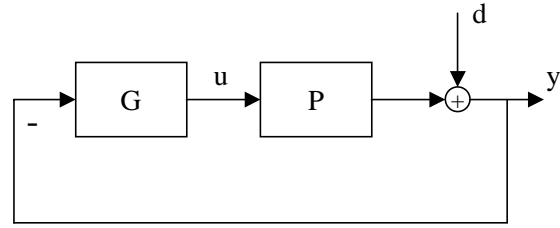


Fig. 4. Feedback system under considerations

The model of the plant P is the model of the vertical dynamics of a high speed ferry properly connected 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 is subjected to one perturbation: wave height (d).

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

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

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 $P(s) \in \tilde{P}$.

$$\left| \frac{P(j\omega)G_c(j\omega)}{1+P(j\omega)G_c(j\omega)} \right| \leq 1.2, \text{ for all } P \in \tilde{P}, \omega \in [0, \infty)$$

2) Plant output disturbance rejection (sensitivity) for any $P \in \tilde{P}$, $\omega \in [0.5, 2]$. The transfer function from the plant output disturbance to the plant output is bounded by:

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

Templates and stability and performance bounds have been computed at the frequencies

$$\omega = [0.5, 0.8, 1, 1.5, 2, 10] \text{ (rad / seg)}$$

The nominal plant is:

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

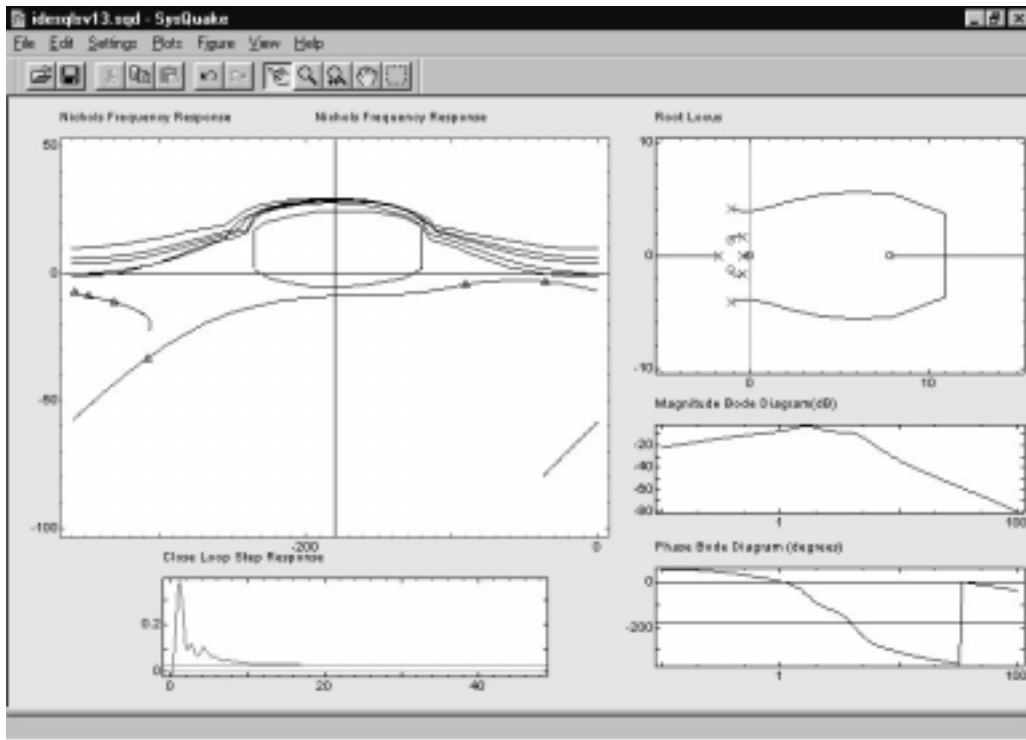


Fig.5. Window of IDESQLS in the beginning of the example.

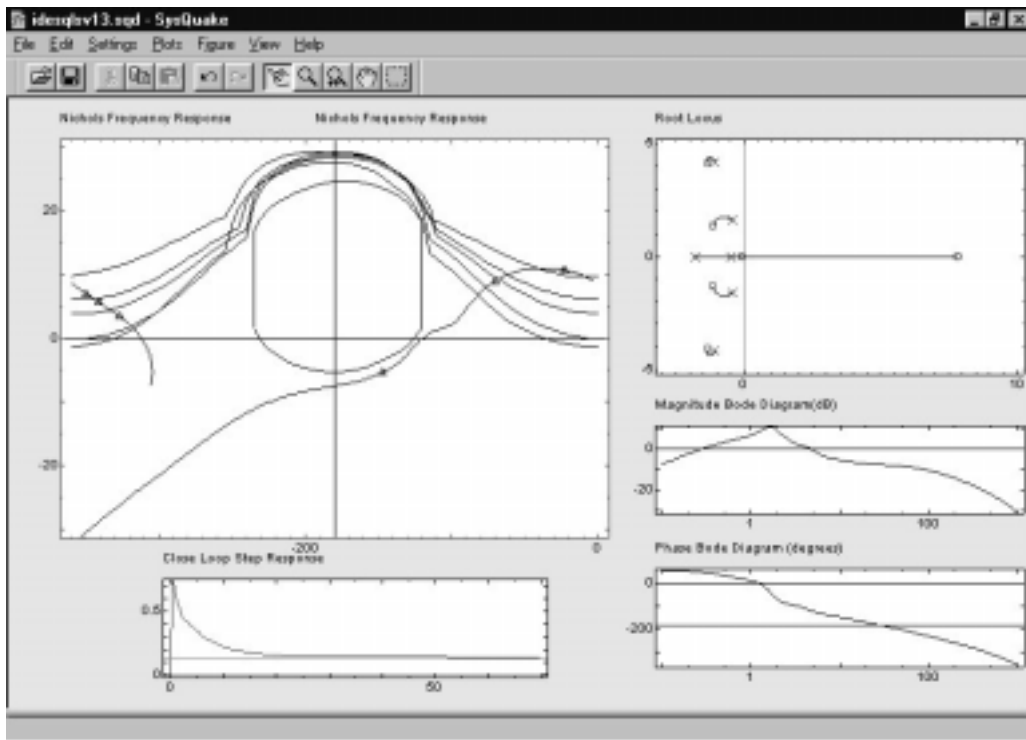


Fig. 6. Window of IDESQLS in the end of the example.

A classical controller was designed for this plant. The nominal controller G_0 is a second order filter that was tuned for the nominal plant solving a non linear optimization problem (Aranda et al., 2001).

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

Figure 5 shows the IDESQLS window 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 it is necessary to increase the gain controller. The user must 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 necessary to add a pair of complex zeros; the user must drag the nominal loop till obtaining a natural frequency $\omega_n=4.32$ rad/seg and a damping factor $\delta=0.31$. The final step to design the controller involves shaping the high frequency response of the nominal loop with the aim that its magnitude falls as fast as possible. The user must place the mouse over the nominal loop and drag the nominal loop till obtaining $\delta=0.8$ y $\omega_n=1000$. The final controller is

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

These modifications in Nichols frequency response are updates in 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 allows our students to understand more quickly and better the synthesis of controllers using QFT methodology. IDESQLS provides the designer with other well-know tools for analysis in order to verify the results of modifications that he inserts into nominal open-loop in Nichols chart. So the design and analysis phases are merged into one, and the student can see immediately the effect of modifying the parameters.

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

Acknowledgements: This research has been supported by CICYT in Spain under contract DPI2000 - 0386 - C03 - 01.

REFERENCES

- Aranda, J., J.M. de la Cruz, J.M. Díaz, B. de Andrés, P. Ruipérez, S. Esteban, J.M. Girón. (2000) Modelling of a High Speed Craft by a Non-Linear Least Squares Method with Constrints. *Proceedings of 5th IFAC Conference on Manoeuvring and Control of Marine Crafts MCMC2000*. Aalborg. pp. 227-232.
- Aranda, J., J.M. Díaz, P. Ruipérez, T.M. Rueda, E. López. (2001). Decreasing of the motion sickness incidence by a multivariable classic control for a high speed ferry. *Proceedings of IFAC Conference on Control Applications in Marine Systems*. CAMS2001. Glasgow. UK. 18th-20th July.
- Borghesani, C., Y. Chait and O. Yaniv. (1994). *Quantitative Feedback Theory Toolbox - For use with MATLAB*. 1st Edition. The Math Works. Inc.
- De la Cruz, J.M., J. Aranda, J.M. Díaz, P. Ruipérez, A. Marón. (1998). Identification of the vertical plane motion model of a high speed craft by model testing in irregular waves. *Proceedings of IFAC Conference CAMS'98 Control Applications in Marine Systems*. Fukuoka. pp. 277-282.
- Esteban, S., J.M. Girón-Sierra, J.M. de la Cruz, B. de Andres, J.M. Díaz, J. Aranda. (2000). Fast Ferry Vertical Accelerations Reduction with Active Flaps and T-Foil. *Proceedings of 5th IFAC Conference on Manoeuvring and Control of Marine Crafts MCMC2000*. Aalborg. pp. 233-238.
- Horowitz, I. M. (1963). *Synthesis of Feedback Systems*. Academy Press, New York.
- Horowitz, I. M. (1972). *Synthesis of Feedback Systems with large plant ignorance for prescribed time-domain tolerance*. Int. J. Control, 16(2), pp. 287-309
- Pigué, Y. (1999). *Sysquake User Manual, version 1.0*. Calerga. Lausanne (Switzerland)