RESEARCH PAPER

ROBUST PID CONTROLLER DESIGN FOR A CHEMICAL PROCESS USING QUANTITATIVE FEEDBACK THEORY (QFT)

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Abstract
It is challenging to maintain enough stability margins and performance characteristics for closed loop systems because the majority of practical systems are characterized by high levels of uncertainty. Designing robust control for uncertain plants is required because traditional control cannot guarantee system performance if plant parameters change. Quantitative Feedback Theory (QFT) has proven to be the most effective approach among the different approaches put forth to address this issue, particularly when dealing with substantial parametric uncertainty. QFT's ability to handle both phase information and significant parametric uncertainty is one of its features. The two-degrees-of-freedom structure is typically used to define the feedback system for QFT purposes.
In industrial control systems, a PID controller is a common generic control loop feedback mechanism. A continuous stirred tank reactor, or CSTR, is a type of chemical system found in many chemical processing facilities. In a CSTR, two chemicals are combined and react to create a concentrated product compound. Because the reaction is exothermic, heat is produced, which slows it down. The product concentration can be adjusted by varying the temperature by the introduction of a coolant flow rate.

Keywords: Robust Control, PID Control, Continuous stirred tank reactor, Quantitative Feedback Theory (QFT)

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Introduction

Because of their related simplicity and ease of implementation, from many years, PID controllers have dominated the process control industry. Research interests have always been driven by the need for improved control strategies to achieve better performance through process control. Choosing how much of the proportional, integral, and derivative components are needed at the controller's output is part of the tuning process for PID controller design.
There is always a compromise in the design of PID controllers because it requires obtaining the P, I, and D components. Finding the ideal values for the PID controller's parameters has never been easy. Although a lot of novel tuning methods have been created for PID controller design, there is still room for improvement. Depending on the plant model, different control tactics are employed when designing the control system [5]. The design is robust if it functions well when the plant's dynamics deviate significantly from the design values. Robust control addresses uncertainty directly via its controller design methodology. The robust control technique known as Quantitative Feedback Theory (QFT) systematically addresses the impacts of uncertainty. The control design of SISO (Single Input Single Output) or MIMO (Multiple Input Multiple Output) uncertain systems, including the nonlinear and time changing instances, is done using QFT, a graphical loop shaping technique.
Isaac Horowitz created QFT, a frequency domain method that uses the Nichols chart (NC) to provide a desired resilient design over a certain plant uncertainty region. QFT provides several advantages over other robust control techniques. The two-degrees-of-freedom structure is typically used to define the feedback system for QFT purposes. A common control loop feedback mechanism in industrial control systems is the proportional-integral-derivative (PID) controller. A PID controller computes and then outputs a corrective action that can modify the process in an effort to fix the discrepancy between a measured process variable and a desired set-point.

BASICS OF PID CONTROL SYSTEM

The three terms proportional (P), integral (I), and derivative (D) make up a PID controller. The total of the three term actions can be used to broadly interpret its behavior. The I term removes the steady state error, the D term enhances the control system's behavior during transients, and the P term provides a quick control response and a potential steady state error.

Parallel Form

It is evident that the P, I, and D channels are unbundled and respond to the error signal.

$$T.\ F1= Kp*\left(\frac{Ti*Td*s^2+Ti*s+1}{Ti*s}\right) \quad (1)$$

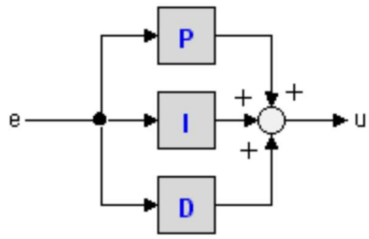

Fig.1: parallel form of PID

Series Form
The control equation for a PID controller in series form, sometimes referred to as interacting form,

$$u = kp(1+\frac{1}{Tis})(1+Tds)e$$

The associated block diagram depiction shows how the controller actions (P, I, and D) behave in a dependent manner.

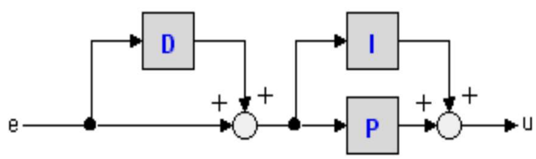

Fig.2: Series form of PID

$$T.F2= kp*(1+\frac{1}{Ti*s})*(1+s*Td) \quad (2)$$

III. QFT BASIC CONCEPTS

QFT is a particularly useful control system design technique when plant characteristics vary over a broad range of operating conditions. The core concept of QFT is defining and taking into account the quantitative relationship between the amount of control effort to be used and the amount of uncertainty to be dealt with during the control design process.

The Quantitative Feedback Theory (QFT) method offers a frequency-domain based design solution to feedback control problems with high performance goals. This approach allows the dynamics of the plant to be described using either frequency response data or a transfer function with a blend of parametric and nonparametric uncertainty models.

The basic concept of QFT is to convert design specifications at closed loop and plant uncertainties into tight stability and performance bounds on open loop transmission of a nominal system, and then apply loop shaping to build a controller.

IV. CONTROLLER SYNTHESIS PROCEDURE

Design Steps for PID Controller are as follows

- Translation of TDS to FDS (Time Domain Specification to Frequency Domain Specification)
- Generation of the Plant Set.
- Generation of the Template.
- Selection of Nominal Plant.
- Generation of Stability Bounds
- Generation of Tracking Bounds
- Grouping of Bounds
- Intersection of Bounds
- Loop shaping (Design of a Controller)
- Prefilter Design

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V. CSTR process

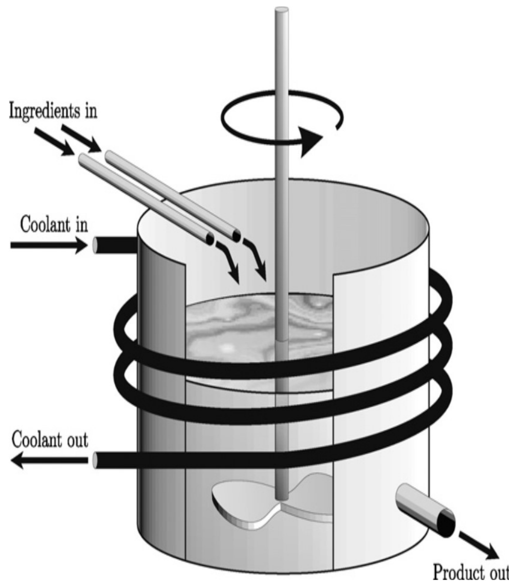

Fig. 3: CSTR process

As a suitable test for TSK fuzzy control, ANFIS control, and PID control, the continuous stirred tank reactor (CSTR), a chemical system available in many chemical processing facilities, was used. Knowing that two chemicals are mixed together in the CSTR and react to produce a concentrated product compound is adequate.
The system is schematically illustrated in Fig. 3. The exothermic property of the reaction slows it down by producing heat. By introducing a coolant flow rate, the temperature as well as the product concentration, can be changed. This section presents a robust PID controller architecture for a first order process with dead time (FODT process). The majority of over-damped processes can be effectively modeled by a first-order system with a time-lag element in the sequence that follows.

$$G(s) = \frac{K * e^{-Ls}}{1+T} \tag{3}$$

Where K, T, and L stand for the system gain, time-lag, and time-constant, respectively. The CSTR model of temperature variations for the change in solution concentration is found in equation (3). The transfer function that follows can be used to approximate it into a FODT process. [7]

$$G_h(S) = \frac{0.5}{100S+1} * e^{-45s} \tag{4}$$

$$G_l(S) = \frac{0.25}{110S+1} * e^{-35s} \tag{5}$$

Performance specifications:
1. Stability Specifications: Gain margin > 5db and Phase Margin=450
2. Tracking Specifications: 200s ≤ rise time≤220s and 0% Overshoot.

VI. Design Steps

Conversion of frequency domain specifications to time domain specifications.

The following are the corresponding transfer functions for the upper and lower specifications:

$$Tl(s) = \frac{0.00001844}{s^3 + 0.1082s^2 + 0.002626s + 0.00001844} \quad (6)$$

$$Tu(s) = \frac{0.00332s + 0.0002756}{s^2 + 0.0332s + 0.0002756} \quad (7)$$

It represents the targeted system performance parameters in the frequency domain as well as the plant's characteristics. The output y (t) in many control systems needs to fall between

y(t)u for the upper bound and y(t)L for the lower bound A step input signal is the basis for the traditional time-domain figures of merit. They are tr rise time, tp peak time, ts settling time, and mp peak overshoot. The upper and lower bounds for corresponding system performance criteria in the frequency domain are Bu and BL, respectively.

For a stable linear-time-invariant (LTI) minimum-phase plant, an LTI compensator may be constructed to meet the required control system performance standards, provided that the control system has minimal sensor noise and adequate control effort authority. Figure 4 [5] displays the frequency response of the performance criteria.

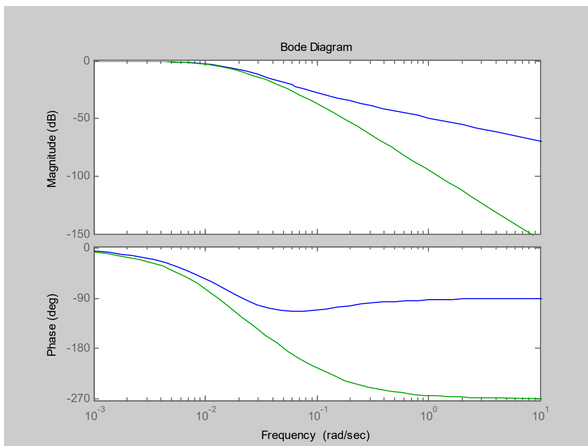

Fig 4: Bode plot

2. Plant Templates

Plots showing plant sets' magnitude versus phase for different frequencies are templates. As seen in figure Generation of templates, templates are created at predetermined intervals that visually represent the Nichols chart's plant parameter uncertainty zone. which characterize the uncertainty of the structured plant parameter

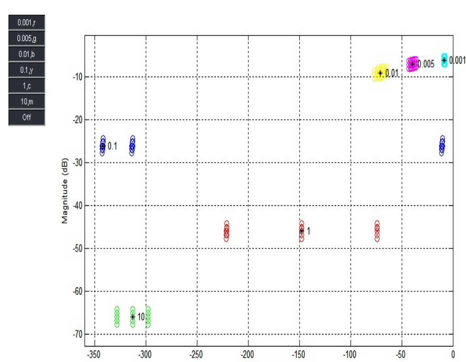

Fig 5: Plant Template

3. Stability bounds

It is commonly known that a circle is formed in the Nichols Chart when the magnitude of T (jw) ≤ ML. A minimum damping ratio for the dominant roots of the closed-loop system is identified by the time- and frequency-domain system performance parameters. This translates to a limit on the value of Mp = Mm. This limit on Mp = ML creates a zone on the NC that the templates and loop transmission functions cannot pass through at any frequency. The U-contour, also known as the universal high-frequency boundary (UHFB) or stability bound, is the boundary of this area.

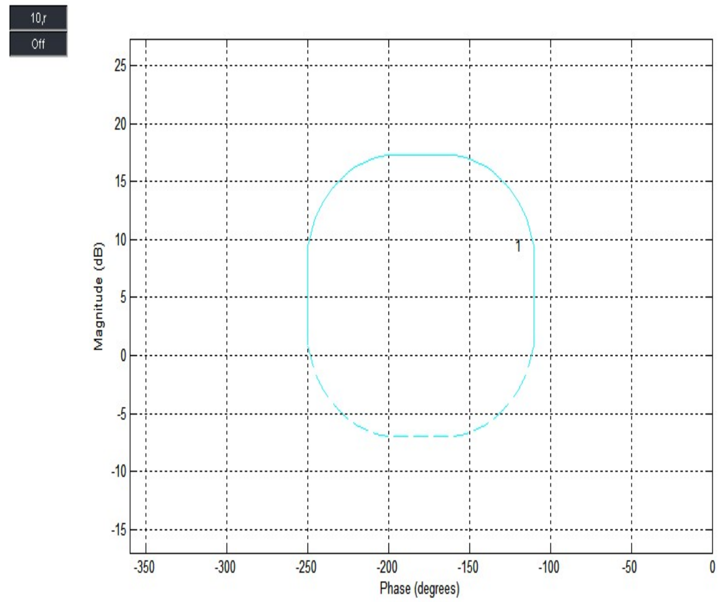

Fig. 6: Stability Bounds

4. Tracking Bounds
Function that tracks the upper and lower limit curves Different plant sets and frequency produce different bounds. The Matlab QFT tool is used to produce tracking boundaries.

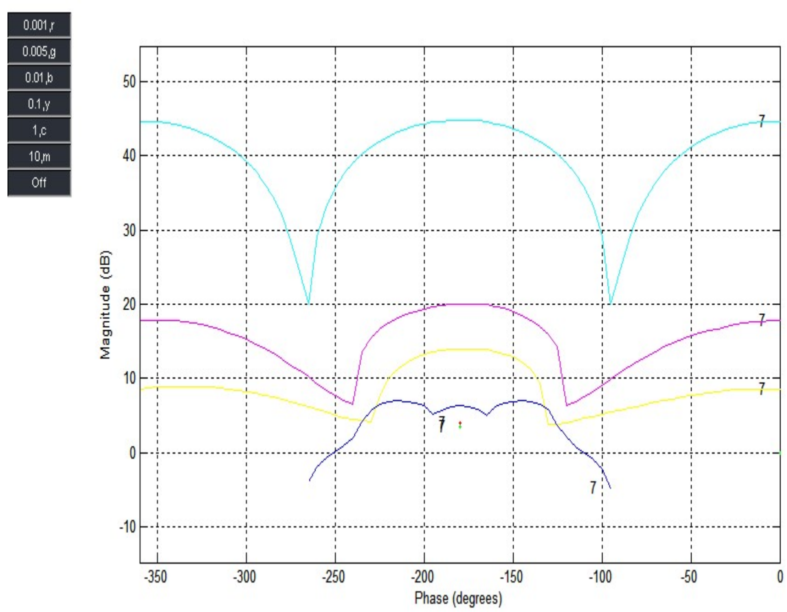

Fig. 7: Tracking Bounds

5. Grouping of bounds

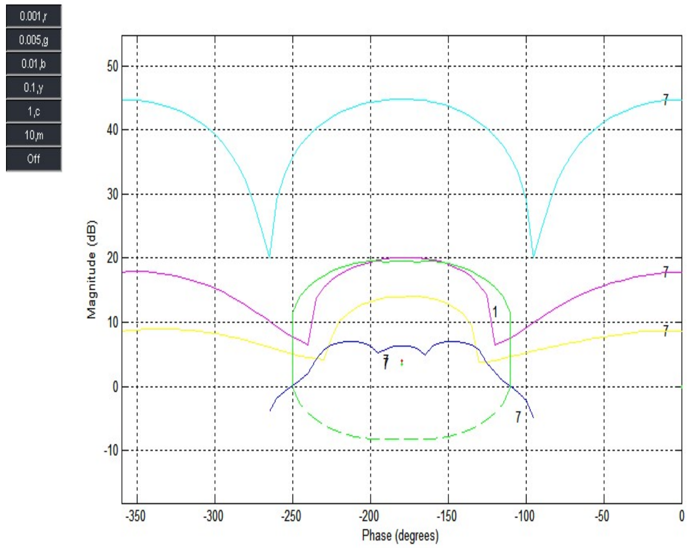

Fig. 8: grouping of Bounds

6. Intersection of Bounds

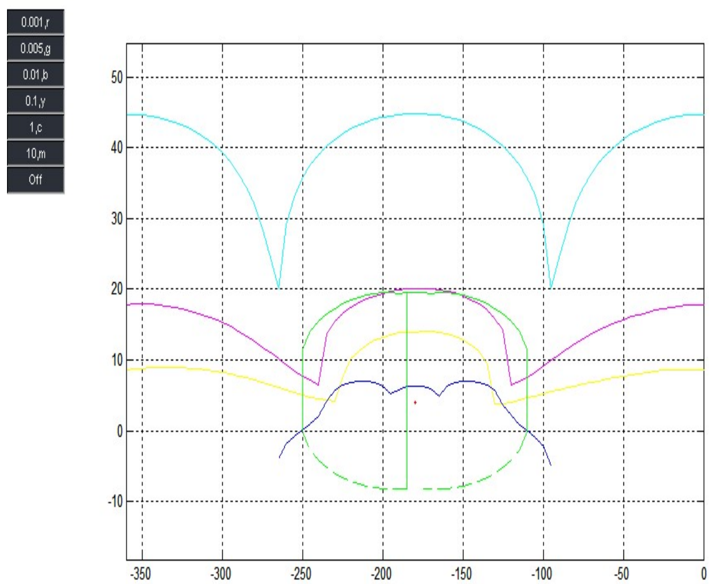

Fig. 9: Intersection of bounds

7. Loop Shaping

The goal of the loop shaping design technique is to select a controller that will give the loop transfer function the desired form. It is a crucial design stage that involves forming the open loop function to establish the parameters specified in the design specifications. The QFT Matlab toolbox can be used for manual loop shaping.

The NC's nominal loopL0(s) and frequency limitations are taken into account when designing the controller. Now, in a process known as Loop Shaping, the designer starts to introduce controller functions (G(s)) and adjust their parameters until the optimal controller is achieved without going against the frequency limitations. Figure 10 illustrates the loop shaping with nominal plant.

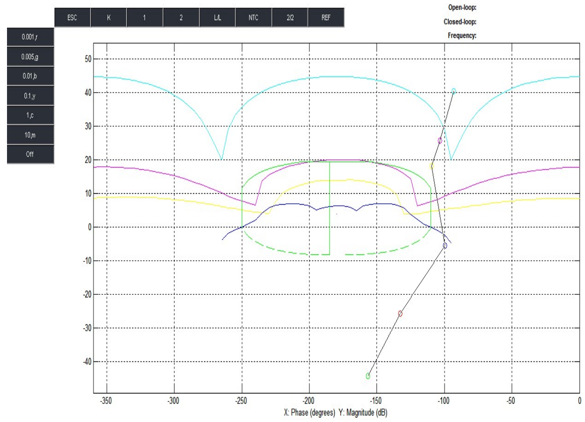

Fig. 10: Loop shaping

The controller obtained after loop shaping is

$$c(s) = \frac{0.2812(3.22S^2 + 51.91S + 1)}{S} \tag{9}$$

8. Filter Design

In order to keep desired tracking performance specifications,
Using Matlab QFT toolbox prefilter is designed

$$F(S) = \frac{1}{122.9S + 1} \tag{10}$$

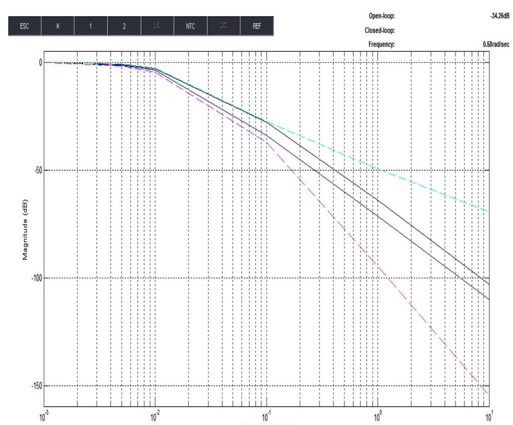

Fig. 11: Prefilter Design

Following manual loop shaping, we obtained the QFT elements, which represent the controller's transfer function. By comparing these elements with the parallel PID controller's transfer function (eq. 1), we can determine the PID parameters. Therefore, the controller's transfer function is

$$c(s) = \frac{0.2812(3.22S^2 + 51.91S + 1)}{S} \tag{11}$$

The PID parameters are as follows
Ti=51.91, Td=0.060, Kp=14.59

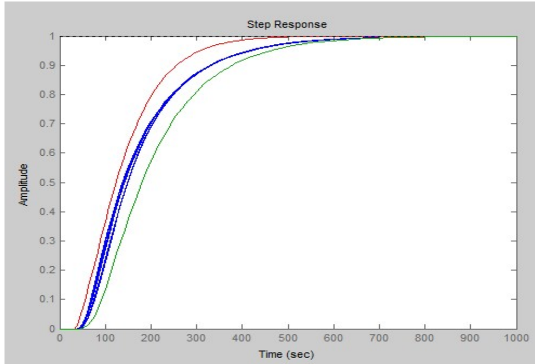

Fig. 12: Step response of all systems.

VI. CONCLUSION

In control, lead and lag compensators, as well as traditional control methods, are widely utilized. It is necessary to build a sturdy controller for uncertain plants. The current H-2, H∞, and μ-synthesis control systems are only suitable for single input single output (SISO) and are unable to manage significant uncertainty.

LTI frameworks large parameter uncertainty cannot be managed by the aforementioned techniques, and the majority of them are suitable for SISO LTI system designs. Classical control theory-based techniques, known as QFT, which operate in the frequency domain and can manage high parameter uncertainty, overcome the shortcomings of conventional and current control theory. We created a PID controller using the QFT approach for an industrial application, such as an example of a continuous stirred tank reactor. We obtain the tracking requirements using the prefilter design.

References:

1. R. G. Cameron, "Control systems engineering, I. J. Nagrath and M. Gopal, Wiley, New York, 1983. Price: £11.40," Optimal Control Applications and Methods, vol. 6, no. 4, pp. 419–419, Oct. 1985, doi: 10.1002/oca.4660060408.
2. G. G. Devadhas, S. Pushpakumar, and R. R. Hemamalini, "An intelligent robust gain schedule controller design for a nonlinear chemical process," 2011 International Conference on Signal Processing, Communication, Computing and Networking Technologies, pp. 705–711, Jul. 2011, doi: 10.1109/icsccn.2011.6024642.
3. M. Garcia-Sanz, "Quantitative Feedback Theory," Encyclopedia of Systems and Control, pp. 1787–1794, 2021, doi: 10.1007/978-3-030-44184-5_238.
4. I. Horowitz, "Quantitative Feedback Theory (QFT)," 1988 American Control Conference, pp. 2032–2037, Jun. 1988, doi: 10.23919/acc.1988.4790059.
5. C. H. Houpis, S. J. Rasmussen, and M. Garcia-Sanz, Quantitative Feedback Theory. CRC Press, 2018. doi: 10.1201/b15907.
6. O. Yaniv, I. Horowitz, "Quantitative feedback theory reply to criticisms", INT.J. CONTROL, 1987, VOL. 46, No-3, page no. 945-962.
7. G.Glan Devadhas," Robust Temperature Controller Design for a nonChemical process using Quantitative feedback theory" International Journal of Engineering Science and Technology, Vol. 2(10), 2010, 5831-5837
8. J. C. Doyle, "Quantitative Feedback Theory (QFT) and Robust Control," 1986 American Control Conference, pp. 1691–1698, Jun. 1986, doi: 10.23919/acc.1986.4789202.
9. Wenhua Chen, "Plant template generation in quantitative feedback theory," UKACC International Conference on Control (CONTROL '98), vol. 1998, pp. 810–815, 1998, doi: 10.1049/cp: 19980333