Robust Control of a Galvanometer : A Feasibility Study

Myoung-Soo Park, Young-Chol Kim, and Jae-Won Lee

Abstract : Optical scanning systems use galvanometers to point the laser beam to the desired position on the workpiece. The angular speed of a galvanometer is typically controlled using Proportional+Integral+Derivative (PID) control algorithms. However, natural variations in the dynamics of different galvanometers due to manufacturing, aging, and environmental factors (i.e., process uncertainty) impose a hard limit on the bandwidth of the galvanometer control system. In general, the control bandwidth translates directly into efficiency of the system response. Since the optical scanning system must have rapid response, the higher control bandwidth is required. Auto-tuning PID algorithms have been accepted in this area since they could overcome some of the problems related to process uncertainty. However, when the galvanometer is attached to a larger mechanical system, the combined dynamics often exhibit resonances. It is well understood that PID algorithms may not have the capacity to increase the control bandwidth in the face of such resonances. This paper compares the achievable performance and robustness of a galvanometer control system using a PID controller tuned by the Ziegler-Nichols method and a controller designed by the Quantitative Feedback Theory (QFT) method. The results clearly indicate that — in contrast to PID designs — QFT can deliver a single, fixed controller which will supply high bandwidth design even when the dynamics is uncertain and includes mechanical resonances.

Keywords : PID algorithm, quantitative feedback theory, galvanometer, robust control

I. Introduction

This paper focuses on a specific laser system, a Scriba ND:YAG laser [1], used to scribe letters and figures into material. This system has a galvanometric optical scanning mechanism which can engrave quickly and accurately. Unfortunately, high angular speeds of the galvanometer tend to excite structural vibrations of the workstation which result in longer settling times for steady-state focusing accuracy. Presently, PID algorithms with some modifications are the controller of choice in applications. To avoid excitation of these resonances, the PID control bandwidth is typically limited to lie well below the frequency of the first resonance. Naturally, such a limit sacrifices the efficiency of the system. Moreover, a typical PID galvanometer controller is tuned by a skilled person in the factory for the given specifications [2]. Therefore, engineers who are not expected to be skilled in this procedure cannot re-tune the PID parameters whenever aging and environmental changes require it.

As alternatives to PID control design, there are numerous robust control design methods that do not require tuning. With these methods, once the possible variations in the process dynamics are quantified, a single, fixed controller is designed to meet the desired performance in spite of the uncertain dynamics. This is refereed to as a *robust performance* problem. A key advantage of these methods is that the end users need not worry about tuning.

This paper describes the application of QFT, a robust control design method which recently was successfully used in similar design problems [3-9]. It is comprised of six sections. The second section describes issues related to identification of the galvanometer dynamics. The third section defines the closed-loop control design problem. The fourth section discusses application of a tuned PID algorithm and its robustness against variation in the galvanometer dynamics. The fifth section discusses the application of QFT and the robustness of its design against variation in the galvanometer dynamic. Finally, section six concludes this paper and section seven includes relevant references.

II. Identification of the open-loop dynamics

In a typical system, the identification of the open-loop plant dynamics P (see Fig. 1) is a first step to design a controller with improved performance. In our setup, a small galvano- meter and a rotational variable differential transformer (RVDT) were used in place of an actual Scriba scanning system because a Scriba was not available during this study.

In Fig. 1, Y' and Y are the output signal in voltages and in degrees respectively. In addition, C(s) is the converting constant from the signal Y' to the angle Y. The input chirp signal U which is generated by Siglab 20-22 [10] and the output RVDT signal Y' used for identification are shown in Fig. 2.

The input signal and the output signal (Y' in Fig. 1) were fed to a SigLab 20-22[10] which identified very accurately the open-loop transfer function by using the broad-band FFT technique.

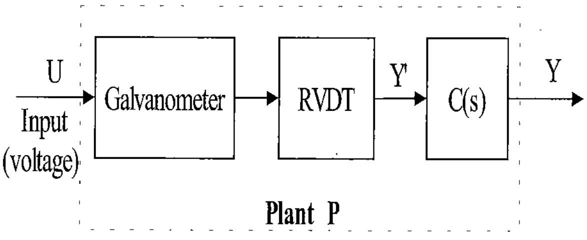

Fig. 1. Block diagram for the open-loop plant identification.

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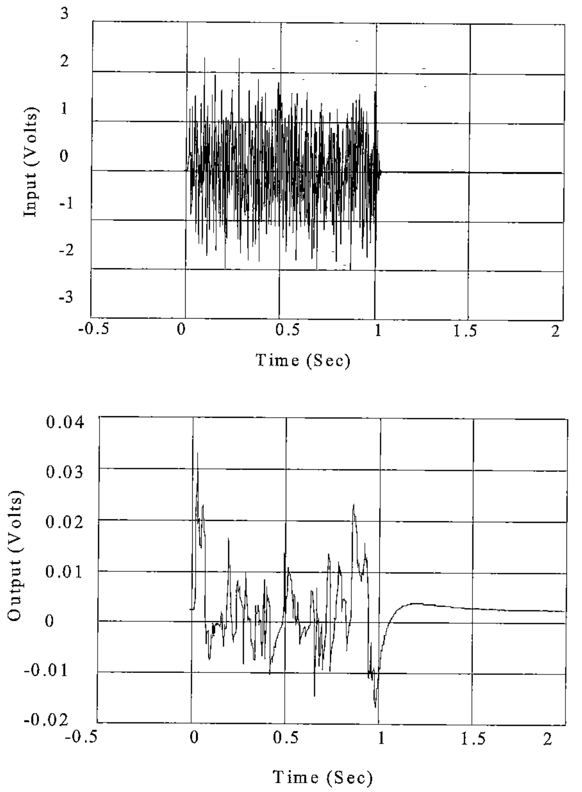

Fig. 2. The chirp input signal (top) and the RVDT output signal (bottom).

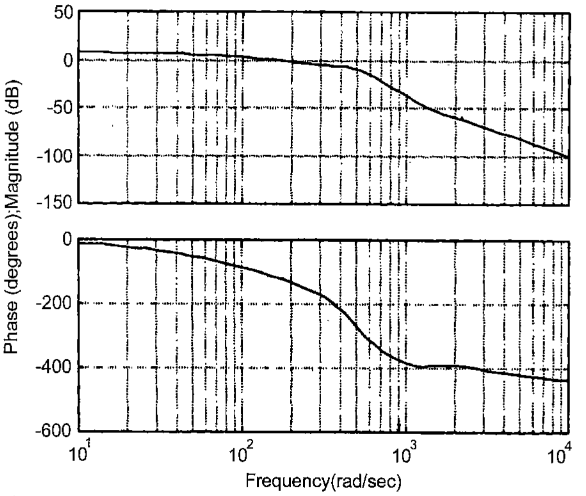

Fig. 3. The bode plot for the plant P(s).

The identified open-loop function P(s) is given by

$$P(s)=\frac{-2.36\cdot\left(\frac{s^2}{1.959x10^6}+\frac{s}{1.967x10^3}+1\right)\left(\frac{s}{1.156x10^3}-1\right)}{\left(\frac{s^2}{1.428x10^6}+\frac{s}{8.897x10^2}+1\right)\left(\frac{s}{3.482x10^2}+1\right)\left(\frac{s}{7.255x10}+1\right)\left(\frac{s^2}{2.500x10^5}+\frac{s}{8.333x10^2}+1\right)} \tag{1}$$

Note that the steady state magnitude in this equation is converted from the voltage (0.063 volts) to the angle (2.36 degrees) by multiplying C(s) (i.e., C(s) = 2.36/0.063). The Bode plot of plant P(s) is shown in fig. 3.

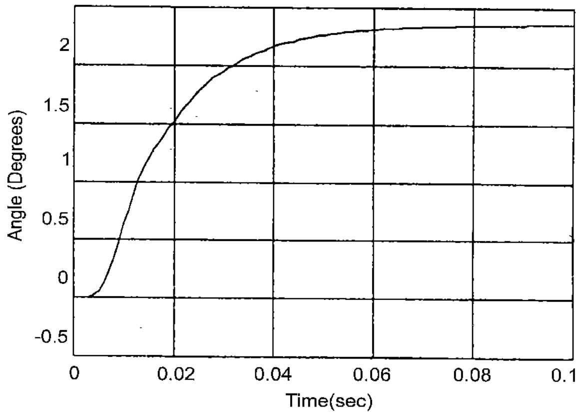

Fig. 4. Simulated open-loop step response of the galvanometer angle.

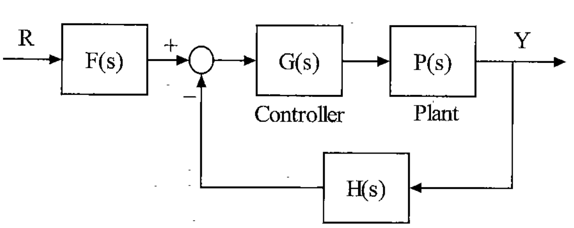

Fig. 5. The closed-loop feedback system.

On the other hand, the unit step response can be obtained by computer simulation as shown in Fig. 4. It resulted in a steady state gain 2.36, no overshoot, and a 4% settling time of about 0.055 seconds.

III. The closed-loop control design problem

Consider the closed-loop configuration shown in Fig. 5. Note that although the pre-filter F(s) was not used in this paper (i.e., F(s)=1), such elements and feedforward controllers can be used to further improve performance in applications.

In Fig. 5, R and Y represent the input signal and the output angle respectively. Note that the feedback constant H(s) is 0.063/2.36. For comparison purpose, the following closed-loop specifications are considered :

- Settling time (4%) should be less than 0.03 seconds.
- Overshoot should be less than 5%.
- Gain margin should be greater than 5.8 dB.
- Phase margin should be greater than 55°.
- Open-loop bandwidth of 600Hz.

This is the same specification as the actual one which is currently applied by a scanner manufacturing company (General Scanning Co., in U.S.A.)[2].

IV. PID design

PID controllers are the most widely used class of controllers in industry. A popular PID off-line tuning method is the Ziegler-Nichols method [11]. It is also the basis for PID auto-tuning algorithms. Application of the Ziegler-Nichols method to design of our PID controller results in a system with 0.052 seconds 4% settling time and 15% overshoot which does not meet the given performance specifications as shown in Fig. 6. The designed Ziegler-Nichols controller has the following equation:

$$G_{ZN}(s) = 20.7167\left(1 + \frac{1}{0.0103s} + 0.0026s\right) \tag{2}$$

It is conceivable that a skilled engineer can further tune the above PID controller by trial and error to meet the given specifications. One such design is

$$G_{PID}(s) = 27\left(1 + \frac{1}{0.015s} + 0.002s\right) \tag{3}$$

Indeed, Fig. 7 shows that the original design by Ziegler-Nichols method can be tuned to satisfy the given specifications where the setting time is less than 0.03 seconds and overshoot is less than 5%.

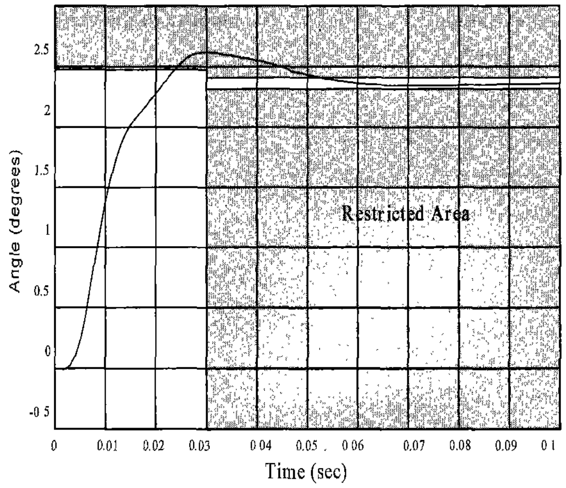

Fig. 6. Galvanometer closed-loop step response the with Ziegler-Nichols PID controller $G_{ZN}(s)$.

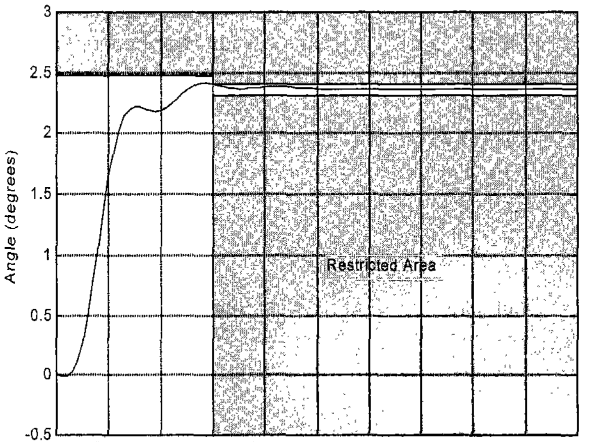

Fig. 7. Galvanometer closed-loop step response with the tuned Ziegler-Nichols PID controller $G_{PID}(s)$.

The main drawback of this design approach is that it cannot guarantee robust stability and performance with complex plant dynamics. To illustrate this point, suppose that the two slowest poles in the nominal open-loop plant vary each by ±2.5% about their nominal values in Eq. (1). In addition, assume that when the galvanometer is attached to the laser workstation, there is a mechanical resonance at 500Hz. The new open-loop plant dynamics is described by the family

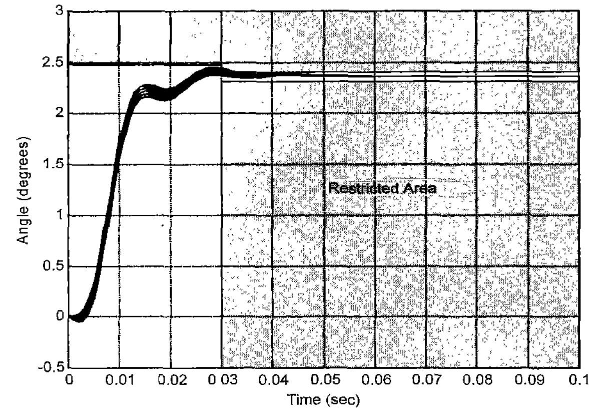

Fig. 8. Galvanometer closed-loop step responses with the tuned Ziegler-Nichols PID controller $G_{PID}(s)$ and the uncertain dynamics.

$$P(s) = \frac{-2.36\cdot\left(\frac{s^2}{1.959x10^6} + \frac{s}{1.967x10^3} + 1\right)\left(\frac{s}{1.156x10^3} - 1\right)}{\left(\frac{s^2}{1.428x10^6} + \frac{s}{8.897x10^2} + 1\right)\left(\frac{s}{3.482x10^2} + 1\right)\left(\frac{s}{7.255x10} + 1\right)\left(\frac{s^2}{2.500x10^5} + \frac{s}{8.333x10^2} + 1\right)} \tag{4}$$

The step responses of several possible plants in the family (Eq. 4) are shown in Fig. 8. The design does not appear to be robust with respect to such variations. The reason is clear from that the PID design in (3) did not consider the plant uncertainties on p_1 and p_2.

V. QFT design

The QFT is an engineering control design method. It focuses on the design of a single, fixed control to meet closed-loop specifications in spite of open-loop process uncertainty and/or unknown disturbances. The single, most important aspect of a QFT controller is that robustness is guaranteed a priori with the minimum possible control bandwidth.

In QFT, the engineer tradeoffs the order of the controller between controller complexity, robustness and achievable specifications. For comparison purposes, our design has the same order as the PID controller. Using the QFT Toolbox [12], the controller (Eq. 5) has been designed in Nichols chart as shown in Fig. 9, wherein we chose working frequencies (1, 10,

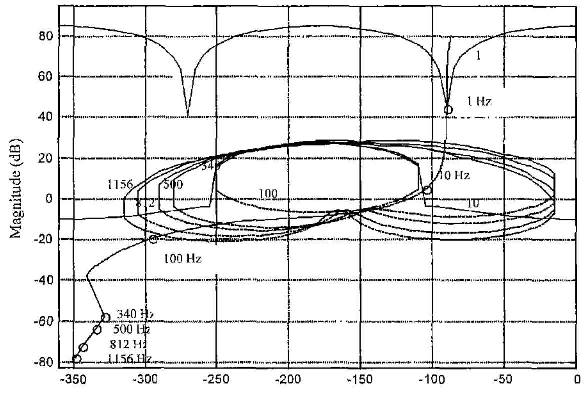

Fig. 9. QFT bounds and loop transmission.

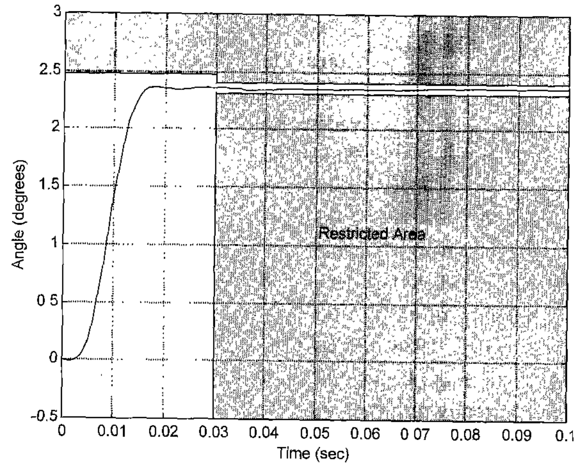

Fig. 10. Galvanometer closed-loop step response with $G_{QFT}(s)$.

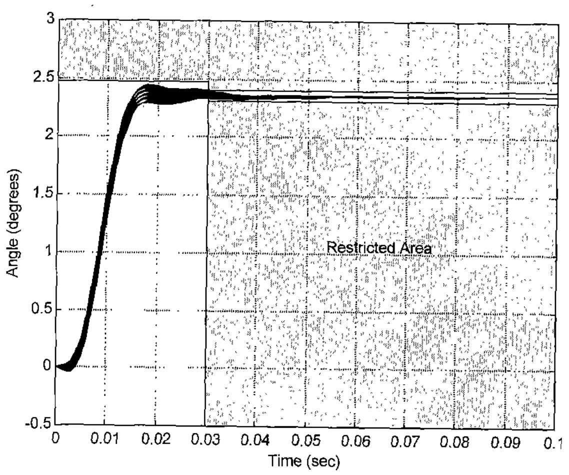

Fig. 11. Galvanometer closed-loop step responses with $G_{QFT}(s)$ and the uncertain dynamics.

100, 340, 500, 812 and 1156Hz) which are denoted in this figure. It is clear that the plot at each chosen frequency satisfies the specified bound that is derived from the given specifications. The details of QFT design are referred to [3,12].

$$G_{QFT}(s) = \frac{3.375 \cdot 10^{6} \cdot \left(\frac{s}{69}+1\right)\left(\frac{s}{900}+1\right)}{\left(\frac{s}{0.0005}+1\right)} \quad (5)$$

In both the PID design and this QFT design, no attempt made to make the controllers proper (i.e., more poles than zeros). Hence, the comparison is a fair one. In application, clearly, both designs would have to be augmented with at least one more pole. The step response shown in Fig. 10 satisfies the closed-loop specifications.

Figure 11 proves that with a QFT design the specifications are met even when uncertainty in the dynamics is considered as in Eq. 4.

VI. Conclusions

The QFT design method and the Ziegler-Nichols method for PID controllers were used for design of a high-performance closed-loop galvanometer system. The performance of both designs were compared with respect to possible variations in the process dynamics as expected in applications. While a QFT design guarantees a priori performance robustness against manufacturing tolerances, aging, environmental changes and disturbances, even auto-tuned PID designs cannot provide such a guarantee. The advantage of a QFT design over a PID design is even more apparent if the specifications call for an increased control bandwidth where significant mechanical resonances exists. While PID designs appear to be the approach of choice in industry, we are confident that with the recent advances in the QFT method [6] it will replace PID design in many applications.

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