Tuning and Testing Force Feedback Control for Single-Axis Nanopositioning Stages

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Abstract

This study produces a practical tuning algorithm to tune the force feedback control for nanopositioning systems. The tuning procedure uses standard measures such as bandwidth and oscillation to tune the parameters of the force feedback loop and the outer loop. The study also discusses the impact of each control parameter on the overall performance of the system. The results include experimental data from the stage NPS-X-15A from Queensgate.

Dual Sensor Technology, Force Feedback, Bandwidth, Nanopositioning, Stages

1. Introduction

Nanopositioning stages are used in a wide range of applications [1]. Typically, these stages are driven by piezoelectric actuators and use strain gauges, or capacitive sensors for high precision, to measure the position. The dynamics of these devices are limited by many lightly damped resonances whose frequencies vary with load [2]. Therefore, to guarantee robustness and not excite high frequency dynamics, nanopositioning controllers are designed with low bandwidth; however this restriction is undesirable in many applications [3]. Several techniques exist in literature to tackle the problem of low bandwidth and to increase the speed of nanopositioning stages; see for example [4-6].

Force feedback control has been introduced as an effective control solution for nanopositioning systems to achieve high bandwidth and simultaneously increase robustness against load variations [3]. This technology is used only by Elektron Technology and exclusively fitted to some of its Queensgate brand nanopositioning systems. This study gives a systematic tuning approach to exploit its advantages. The study discusses the tuning of the control parameters and gives hints to achieve good overall performance of the system. The study uses frequency response to analyse the performance of force feedback control. The study shows experimental results from the stage NPS-X-15A from Queensgate.

2. Control Architecture

In stages enabled with force feedback there are two sensors: position and force. The position sensor measures the displacement of the stage and the force sensor measures the applied force to the piezoelectric actuator. Accordingly, the control architecture has two feedback loops; see Figure 1. The inner control loop is a feedback loop of the force sensor output which helps to damp the overall resonance dynamics of the system and the outer loop involves the displacement feedback which is used for the position tracking. Therefore, this structure helps to damp the resonances while maintain the bandwidth of the system. In practical implementation the inner controller is usually an integrator of the form $C_f = 1/\tau_f s$ and the outer controller is a PI of the form $C_p = k_p + 1/\tau_p s$. Complementary low and high pass filters of identical crossover frequency are needed because at low frequencies the piezoelectric force sensor is not sensitive. Therefore, the feedback signal is generated from the force sensor above the crossover frequency and from the input signal to the stage u below the crossover frequency. The scaling gains k_f and k_u on the force feedback loop are used to match the scale of the force sensor output with the scale of the stage actuator input u.

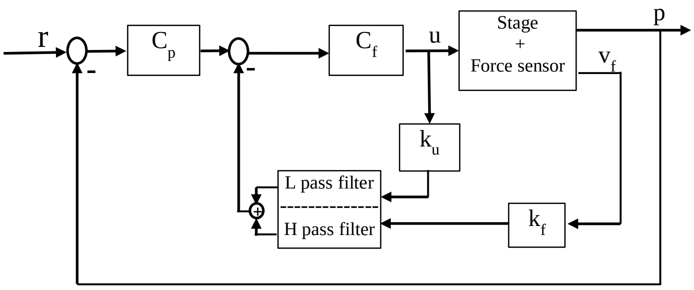

Figure 1: Control architecture of dual sensor technology

2.1. The feedback gain of the force sensor k_f

The purpose of the gain k_f on the force feedback loop is to match the sensitivity of the force sensor with the sensitivity of the actuator. However, increasing this gain to be more than unity makes the tuning of the integral time constant τ_f difficult and counter intuitive, where the relation between the bandwidth of the closed loop system and τ_f becomes nonconventional. Therefore, we recommend to keep $k_f = 1$ and use k_u to scale the sensitivity of the inputs of the two complementary filters. This will have less impact on the tuning of the other parameters because k_u is active only at low frequencies. Therefore, when tuning the τ_f and the PI controller, k_u can be ignored.

2.2. Integral time constant τ_f

The integral time constant determines the bandwidth of the system. It is very important to note that increasing the bandwidth of the system increases the impact of the high frequency dynamics. However, decreasing the bandwidth limits the overall speed tracking of the system. The best practice for tuning this parameter is simply to apply a step command to the internal loop with the outer loop open and bypassing the PI controller. We measure the output from the displacement sensor. We start with a small value for the integral time constant (where clearly the system will exhibit resonant behaviour) and then slowly increase the time constant until the step response is satisfactory. Increasing τ_f above a certain range will bring resonance again in the response.

2.3. The outer loop control parameters

The parameters of the external PI loop can be tuned in the normal way of tuning a PI controller for stages with no force feedback loop. However, few points should be taken into consideration when tuning the PI controller for a system fitted with dual sensor technology:

1- The force feedback control can achieve higher band width and therefore the PI integral time constant τ_p should be tuned to maintain the high bandwidth of the system

2- The presence of the force sensor and the internal force feedback loop makes the stage stiffer. This should be taken into consideration when tuning the PI controller which requires higher proportional gain k_p than the case of a similar stage without a force feedback sensor. However, increasing the proportional gain will magnify the impact of the sensor noise on the response of the system. Generally speaking, increasing the proportional gain k_p will reduce the rise time at the expense of increased noise amplification, oscillations and overshoot.

3. Results

The tuning procedure described in the previous section was demonstrated on a Queensgate NPS-X-15A stage. The stage is fitted with an internal force sensor and the control structure is implemented using the hardware controller NPC-D-5110 from Queensgate. The command signal was applied and the response is measured using the Nanobench software.

The identified open loop frequency response of the stage is shown in Figure 2. The resonance frequency occurs in the range (2-3)x10^4 rad/s. The tuning criteria used are maximum bandwidth with no oscillation. The achieved parameters for this tuning are listed in Table 1.

In order to demonstrate the robustness of the system under load variations, the stage was loaded with 800 g mass under the same tuned controllers. Figure 3 depicts the frequency response of the closed loop system for both cases, the nominal case with no load and with 800 g load.

5. Conclusion

Dual sensor technology has been introduced as an effective control solution to achieve accurate, robust and fast nanopositioning stages. However, to exploit the advantages of this technology, the configuration requires careful tuning and implementation. This paper gives a brief introduction to practical aspects of the tuning and implementation of a specific structure of force feedback control for single axis nanopositioning stages to achieve satisfactory performance.

Table 1: Control parameters tuning

Parameter	Value	Parameter	value
τ_p	4x10^-4	k_f	1
k_p	1	k_u	0.1503
		τ_f	9x10^-5

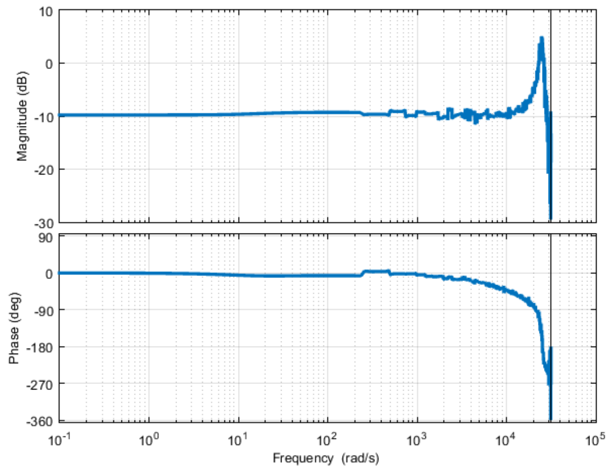

Figure 2: Identified open loop frequency response from the input u to the displacement p.

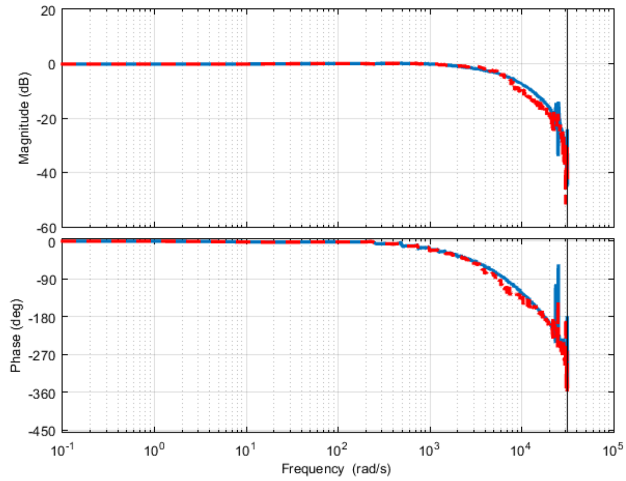

Figure 3: Closed loop frequency response with force feedback control: the nominal case with no load (solid blue line) and the case of 800 g load (dashed red line).

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