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Classical Tuning of Force Feedback Control for Nanopositioning Systems with Load Variations

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Abstract: In nanopositioning systems, force feedback control has been proposed as an advanced control technique to enhance the bandwidth of the system and improve the tracking performance. In direct tracking with force feedback control, the architecture employs an inner force feedback loop to damp the first resonance peak and enhance the bandwidth. The position feedback loop is then used to enhance the tracking performance of the overall system. This paper discusses the practical issues associated with the control design of force feedback. The paper presents hardware results to support the analysis and proposes a systematic tuning method to retain the advantages of the force feedback control in the face of load variations.

Keywords: Nanopositioning, Control, Force Feedback, Dual Sensor Technology

1. INTRODUCTION

Nanopositioning stages are used in many applications such as scanning probe microscopy, atomic force microscopy, lithography and imaging to generate mechanical displacement in microscopic scale (Devasia et al., 2007). These devices, along with their applications, have introduced fundamental change in several scientific areas including biology, chemistry, physics and materials science (see for instance Jandt et al., 2000; Bushan, 2010; Fleming and Leang, 2014, and references therein). In general, these devices employ piezoelectric actuators due to their high resolution and compact size (Xu, 2015). However, piezoelectric nanopositioning stages have challenging characteristics such as creep and hysteresis that limit the capabilities and may degrade the performance (Eielsen et al., 2014). Moreover, the existence of lightly damped resonances in all types of nanopositioning systems, which results from the interaction between the platform and the stiff support flexures, represents a main disadvantage that limits the bandwidth of the closed-loop system (Salapaka et al., 2002). Practically speaking, the bandwidth is limited by the first resonance peak. It has been reported in the literature (e.g., Fleming (2010)), that with feedback only control the bandwidth is usually set to be no more than 2% of the first resonance peak. This is to maintain good performance of the closed-loop system and preserve robustness against load variations. This is a major undesirable limitation for many applications (Clayton et al., 2009). For instance, one of the recent applications that require high bandwidth nanopositioning systems are hard-disk drives (HDD) (Bushan, 2010). In response to this problem several control methods have been proposed in the literature (and are implemented in practice) to damp the first resonance peak and enhance the bandwidth of the closed-loop system, (see for instance Eielsen et al., 2014; Aphale et al., 2007; Das et al., 2014; Fleming and Leang, 2014). The proposed fixed-structure control systems can be divided into four categories; feedback control, feedforward control, iterative control and sensorless control (Devasia et al., 2007). A combination of feedback and feedforward control is also reported by Kara-Mohamed et al. (2015) with promising results. Force feedback technique has been introduced by Preumont (2006); Fleming (2010) and Fleming and Leang (2010) as a new control system to enhance tracking and vibration control in nanopositioning stages with significant improvement in bandwidth. This paper focuses on the practical implementation aspects of the force feedback control and produces a case study with experimental results for a short range stage with force feedback control.

In Section 2, the force feedback control technique is reviewed briefly. Section 3 produces general practical tuning guideline on how to consider frequency response along with time domain analysis to tune the force feedback control and maintain good tracking performance of the stage. In Section 4 a case study is produced to showcase an example of designing force feedback control in the presence of load variations. The conclusion of the paper is presented in Section 5.

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2. FORCE FEEDBACK CONTROL

Force feedback control is based on adding a sensor in addition to the displacement sensor to measure the force applied by the piezoelectric actuator. Accordingly, one of the control architectures that has been suggested by Fleming (2010) is to utilise two feedback loops; see Fig 1. The inner control loop involves the measurement from the force sensor and is designed to achieve damping control and enhance the bandwidth. The outer loop involves the displacement feedback and is used for position tracking. This stands in contrast to "dual sensor control" (as defined by Fleming, 2010) where knowledge of the relative gain of the position and force response is required to achieve correct steady state tracking.

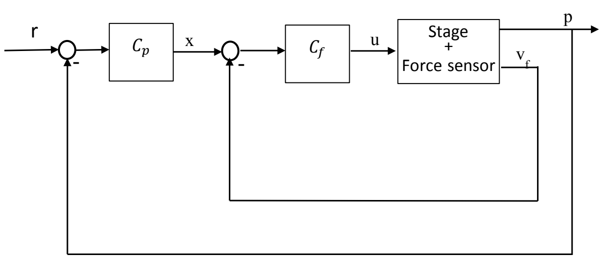

Fig. 1. Control architecture of the force feedback control with direct tracking.

Assuming linearity, the transfer function matrix of the stage from the actuator input u to the two outputs of the system is:

$$G = \begin{bmatrix} G_p \\ G_f \end{bmatrix}, \quad (1)$$

where G_p is the transfer function from the actuator input u to the displacement position p and G_f is the transfer function from the actuator input u to the force sensor output V_f.

The closed-loop response from the command signal r to the displacement position of the stage p is given by:

$$T_{rd} = \frac{G_p C_f C_d}{1 + G_p C_f C_d + G_f C_f}. \quad (2)$$

The transfer function from the output of the PI compensator x to the position of the stage p is given by:

$$T_{xp} = \frac{G_p C_f}{1 + G_f C_f}. \quad (3)$$

Preumont (2006) and Fleming (2010) argue that the key property of the system G_f is that its frequency response has phase lying in the range $[0°, 180°]$. This means that the system can be damped using simple integral control. If the inner controller is chosen to be an integrator of the form $C_f(s) = \frac{1}{\tau_f s}$ then the resulting forward loop transfer function $G_f C_f$ has an infinite gain margin and a phase margin of 90° (i.e., it is passive). An 'optimal' value for τ_f can be chosen based on a root locus argument assuming second order dynamics (Preumont, 2006; Fleming, 2010). In practice, digital implementation and/or any slight misalignment of the sensor invalidates the assumption of passivity. In addition, the presence of higher order dynamics and the requirement for good performance against varying loads invalidates any 'optimal' tuning based on root locus arguments. Nevertheless the control structure works well and can be easily tuned via classical techniques and/or simple step response tests. For most applications it is sufficient to choose the outer loop controller as a PI of the form $C_p = k_p + \frac{1}{\tau_p s}$.

3. TUNING PROCEDURE

Fleming (2010) does not discuss the combined tuning of the force feedback loop and the outer loop. From a practical point of view, tuning of both loops is vital. We propose in this section general guidelines of how the inner and outer loop of the system should be tuned in order to exploit the advantages of force feedback control. In particular we discuss how both time domain and frequency domain requirements should be addressed in the presence of load variations.

3.1 Integral time constant τ_f

The parameter τ_f serves to increase the effective damping of the position response. The best practice for tuning this parameter is simply to apply a step command to the internal loop on x with the outer loop open (i.e., bypassing the PI compensator) and to measure the output from the displacement sensor. For example, one can 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. Therefore, τ_f should be tuned in the range between these two resonant values to achieve the best possible damping. Frequency response of the internal loop from x to p should be used to confirm the quality of the time domain tuning of τ_f. As a measure of robustness, the chosen value τ_f should be tested with reasonable load on the stage. Trials confirm that doing this for one particular load gives good response across all loads lower than the tested load.

3.2 The outer loop control parameters

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

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