Control Engineering Practice 20 (2012) 643–653

Contents lists available at SciVerse ScienceDirect

Control Engineering Practice

journal homepage: www.elsevier.com/locate/conengprac

Robust digital control approach for high performance tunneling current measurement system

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ARTICLE INFO

Article history:
Received 17 November 2010
Accepted 29 February 2012
Available online 1 April 2012

Keywords:
Tunneling current
Robust digital control
Nano-positioning
Piezoelectric actuator
Scanning tunneling microscope
Sensitivity function shaping

ABSTRACT

This paper is devoted to the digital control system design for high performance measurement of tunneling current. A common approach for such applications is to use a conventional Proportional Integral (PI) control. In this paper, a robust digital design method is instead considered, based on combined pole placement with sensitivity function shaping, and allowing for better performance tuning in terms of precision, robustness and disturbance rejection. The resulting control scheme looks like some *enhanced PID* controller, and is validated over an experimental setup, developed in GIPSA-lab (*Grenoble Image Parole Signal Automatique*) research center. The corresponding simulation and experimental results show improved performances with respect to those obtained with the more conventional PI control technique.

1. Introduction

Tunneling current is a quantum mechanical effect: an electron has a non-zero probability of tunneling through a potential barrier (Landau & Lifshitz, 1977). This phenomenon of tunneling current was first observed in early 1980s by Gerd Binnig and Heinrich Rohrer, and appears when an extremely sharp metallic electrically charged tip is approached at the vicinity of the conductive sample surface (distance between tip apex and sample surface in the range of $0.1-1\times10^{-9}$ m) (Chen, 2008). An important application of this tunneling current with the ability to scan the tip against the sample surface was the invention of the scanning tunneling microscope (STM) (Binning & Rohrer, 1986). It was the first member of the family of Scanning Probe Microscopes (SPMs) that can characterize the surface morphology with atomic resolution exploiting different physical phenomena, and in which the so-called Atomic Force Microscope (AFM) has received a particular attention (even from the very beginning Rugar & Hansma, 1990).

Tunneling current is also used to measure accelerations down to submicro-g (Liu et al., 1998; Liu & Kenny, 2001; Rockstad et al., 1996) and to sense sub-micrometer displacements (Blanvillain, Voda, Besancon, & Buche, 2009; Bocko, 1990; Ekinci, 2005). Since the distance between tip apex and sample surface must be less than 1×10^{-9} m to get the tunneling effect, ultrahigh positioning accuracy together with high bandwidth are here major challenges. This means that control has an important role to play in such tunneling applications. The control scheme in most of them is mainly composed of a sensor for the tunneling current measurement and also a regulation feedback loop, having a piezoelectric actuator attached to the tip in order to move it precisely in appropriate direction. Most of such controllers in commercial applications (and more generally in commercial SPMs for similar control problems) reduce to simple ones (mainly Proportional-Integral, PI), where the parameters are fixed manually by the operator. On the other hand, a lot of advances have been provided in SPM control problems by the scientific community (more particularly in AFM) over the last two decades (see references below).

In the same spirit of control improvement, the present work is devoted to the inspection of a *robust design* approach for the control of tunneling phenomenon in the presence of a piezoelectric actuator and a sensor for the tunneling current measurement. An experimental setup has been developed in that respect by the control group of GIPSA-lab (*Grenoble Image Parole Signal Automatique* Lab), in order to analyze the influence of different control techniques on tunneling current measurement. This setup works at ambient atmosphere and is based on STM principles, although the purpose is not necessarily to take images of the surface. Tunneling current is the only measurement in vertical z-direction of STM. During scanning, when the separation between the sample surface and the tip decreases or increases due to variations in the sample topography, the control

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0967-0661/$ - see front matter
http://dx.doi.org/10.1016/j.conengprac.2012.02.010

signal regulates the tunneling current by actuating the tip away from or towards the sample surface.

Notice that in STM applications for instance, the use of simple controllers with manual tuning can result in imaging performances which are not satisfactory (Anguiano, Oliva, & Aguilar, 1998) and this has already motivated dedicated studies: a feedback loop of STM in vertical z-direction with some stability conditions has been presented in Oliva, Anguiano, Denisenko, Aguilar, and Pena (1995) but this analysis was limited to the classical PI control technique, and based on a simplified version of the system model. A step variation in sample surface has been studied in Bonnail (2001) and Bonnail, Tonneau, Jandard, Capolino, and Dallaporta (2004) and a VSC (variable structure control) design methodology in the presence of PI control has been proposed in order to avoid the tip collision with the sample surface. However, tunneling current being of order of nano-amperes, the presence of different sources of noise (Bordoni & Karim, 1994) (thermal noise, shot noise, $1/f$ noise, quantization noise, etc.) as well as sample surface variations highly influence the precision of its measurement. In addition, nonlinearities and physical limitations in the control loop are also limiting factors for the performances, which still motivate further studies.

Notice also that similar problems and control studies about piezoelectric actuation for nanopositioning can be found in various other SPM applications, with purposes of performance improvement. Even though not explicitly handling tunneling effect, some of them can be recalled here for the sake of comparison: Salapaka, Sebastian, Cleveland, and Salapaka (2002) for instance have addressed a robust H_∞ control design approach for the lateral motion of AFM tip in order to achieve both high bandwidth and high precision; Sebastian and Salapaka (2003, 2005) have considered a two-dimensional large-range nanopositioning system and analyzed the performance with Glover McFarlane loop-shaping and robust H_∞ control design; Bhikkaji, Ratnam, Fleming, and Moheimani (2007), Bhikkaji, Ratnam, and Moheimani (2007) have highlighted the problem of lightly damped low frequency resonant mode of piezoelectric actuator and proposed a solution using a positive velocity and position feedback control design methodology; Some inversion-based feedforward control approach in order to enhance the tracking bandwidth has been analyzed in Aphale, Devasia, and Moheimani (2008); The vertical direction control of AFM-scanner with classical PI has been presented in Schitter et al. (2007); High speed imaging of fragile samples with AFM using some dynamic PID controller has been discussed in Kodera, Sakashita, and Ando (2006); In order to enhance the imaging speed of AFM with precision, a model-based open-loop control has first been analyzed (Schitter & Stemmer, 2004); and very recently, a model-based feedback controller with *dual* (instead of single) actuation has been studied in Kuiper and Schitter (in press). A good survey on control issues for nanopositioning in terms of hardware design and control methodologies is proposed in Devasia, Eleftheriou, and Moheimani (2007), while an overview dedicated to AFM can be found in Abramovitch, Andersson, Pao, and Schitter (2007), and about issues in video-rate scanning speed for various SPM applications in Schitter and Rost (2008) and Rost et al. (2009).

But the phenomenon of tunneling current (in vertical z-direction as in STM) has not really been analyzed with some modern robust control design methodology in any of those references.

The goal of the present work is thus to investigate a robust design approach in this context, choosing a method developed since several years in GIPSA-lab (Landau & Karimi, 1998) and based on combined pole placement with sensitivity function shaping, to provide a control design for a better measurement of tunneling current. The desired performance and stability requirements are expressed by means of constraints on the shape of closed-loop sensitivity functions. To the authors' knowledge, such a control design methodology has never been experimented for tunneling current measurement systems so far. The readers can also refer to Voda (2010) and references therein for recent related works.

The working principle with complete description of the considered experimental setup is given in Section 2. The system modeling for controller design is provided in Section 3. Section 4 then presents the control problem formulation, desired performances, robust digital controller design and its performance analysis. In particular a comparison in simulation with results obtained via a classical PI controller is included, as well as a discussion at the light of a *full PID* approach. Experimental results to validate the plant model and to analyze the performance of controllers are presented in Section 5. Finally, Section 6 draws some conclusions.

2. System description

2.1. Working principle

The complete closed-loop control scheme which will be here considered is presented in Fig. 1. The working principle of an STM in vertical z-direction is based on the measurement and control of the tunneling current (i_t) produced between the sharp metallic tip and a biased (v_b) sample surface when the distance (d) between them is less than 1×10^{-9} m. This tunneling current exponentially depends on the distance between tip and sample surface with the following nonlinear relation:

$$i_t(t) = g\cdot v_b\cdot e^{-k\cdot d(t)} \tag{1}$$

where g and k (depending on work functions Φ of the tip and sample surface) are constants. Controlling this tunneling current (i_t) by keeping the distance (d) constant in the presence of external disturbances (noise (n), surface variations (z_S), etc.)

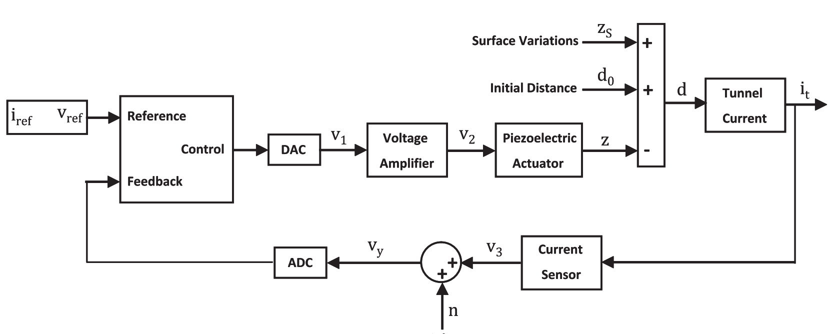

Fig. 1. Complete simulation model with block diagram representation.