Institutionen för systemteknik
Department of Electrical Engineering

Examensarbete

Investigation of Control Approaches for a Rotational Piezo-based Actuator for Accurate Positioning Application Operation at CERN

Examensarbete utfört i Mekatronik
vid Tekniska högskolan vid Linköpings universitet
av

Niklas Ericson

LiTH-ISY-EX--YY/NNNN--SE

Linköping 2016

Department of Electrical Engineering
Linköpings universitet
SE-581 83 Linköping, Sweden

Linköpings tekniska högskola
Linköpings universitet
581 83 Linköping

Investigation of Control Approaches for a Rotational Piezo-based Actuator for Accurate Positioning Application Operation at CERN

Examensarbete utfört i Mekatronik
vid Tekniska högskolan vid Linköpings universitet
av

Niklas Ericson

LiTH-ISY-EX--YY/NNNN--SE

Handledare: **Doktorand Si**
ISY, Linköpings universitet
Mark Butcher
CERN, Geneva, Switzerland

Examinator: **Proffesor Svante Gunnarsson**
ISY, Linköpings universitet

Linköping, 9 april 2016

Avdelning, Institution
Division, Department

Institutionen för Systemteknik
Department of Electrical Engineering
SE-581 83 Linköping

Datum
Date

2016-04-09

Språk
Language

☐ Svenska/Swedish
☒ Engelska/English
☐ ____________

Rapporttyp
Report category

☐ Licentiatavhandling
☒ Examensarbete
☐ C-uppsats
☐ D-uppsats
☐ Övrig rapport
☐ ____________

URL för elektronisk version

http://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-XXXXX

ISBN
—

ISRN
LiTH-ISY-EX--YY/NNNN--SE

Serietitel och serienummer
Title of series, numbering

ISSN
—

Titel
Title

Undersökning av ett problem

Investigation of Control Approaches for a Rotational Piezo-based Actuator for Accurate Positioning Application Operation at CERN

Författare
Author

Niklas Ericson

Sammanfattning
Abstract

Det här som vi har hållit på med är jätteviktigt faktiskt och det vi gjort blev bara sååå bra. Kanske inte helt otippat, men det glass är sååå gott!

Förresten har vi blivit bäst på att skriva rapporter, så nu ska ska vi inte gå in närmare på några detaljer såhär i sammanfattningen.

Nyckelord
Keywords

problem, lösning

Sammanfattning

Det här som vi har hållit på med är jätteviktigt faktiskt och det vi gjort blev bara sååå bra. Kanske inte helt otippat, men det glass är sååå gott!

Förresten har vi blivit bäst på att skriva rapporter, så nu ska ska vi inte gå in närmare på några detaljer såhär i sammanfattningen.

Abstract

If your thesis is written in English, the primary abstract would go here while the Swedish abstract would be optional.

Contents

Notation

Några mängder

Notation	Betydelse
$\mathbb{N}$	Mängden av naturliga tal
$\mathbb{R}$	Mängden av reella tal
$\mathbb{C}$	Mängden av komplexa tal

Förkortningar

Förkortning	Betydelse
CERN	European Organization for Nuclear Research
STM	Scanning Tunneling Microscope
AFM	Atomic Force Microscope
LHC	Large Hadron Collider
PEA	Piezoelectric actuator
PID	Proportional, Integral, Differential (regulator)
DOF	Degrees of Freedom
PBRS	Pseudo Random Binary Sequence

1 Introduction

1.1 Background

The piezoelectric effect is a phenomenon that arises in certain solid materials when an electric potential is generated in response to applied mechanical stress. The effect was first discovered by Jacques and Pierre Curie in 1880 when they found that applying pressure to a quarz crystal generates electrical potential. Today, the effect is commonly encountered in daily life and utilized in for example lighters, buzzers and loudspeakers.

Smart materials such as piezoelectric and magnetostrictive materials are commonly used in precision actuators today due to their ability to convert electrical energy into mechanical energy. Piezoelectric materials have been commercially available for almost 45 years and have become indispensable for the nanopositioning industry [5]. In cases where a relatively small displacement range is required (travel ranges up to 500 μm) a piezo electric device is the actuator of choice due to its fast response, high resolution and its ability to generate large mechanical forces for small amounts of power in compact designs [4].

High precision positioning systems are vital in e.g. scanning tunneling microscopes (STM), atomic force microscopes (AFM) and in semiconductor lithography. In AFM, for instance, high precision positioning is required to control the vertical position of the scanning probe to keep the force constant between the sample surface and the probe tip. An topographical image of the sample is obtained by raster-scanning the probe over the sample surface and plotting the vertical displacement against the probe's x-y position. A positioning system that keeps the force constant down to an atomic-scale resolution is thus inevitable in order to obtain a high resolution image without damaging the sample [4].

In the UA9 Experiment located at CERN (European Organization for Nuclear Research) a high precision positioning system is required for the control of a piezo-actuated rotational stage. The stage uses a piezo electric linear stack actuator to displace a flexible lever arm mechanism which generates the rotational movement.

1.2 Purpose and Goal

Crystalline solids have the ability to constrain the directions that particles take as they pass through, this is commonly called the "channelling" property. The UA9 collaboration at CERN is investigating how tiny bent crystals can help to steer particle beams in modern hadron colliders such as the Large Hadron Collider (LHC) [7]. In high energy colliders, such as the LHC, particles drift outwards creating a beam halo. These particles surrounding the beam, can be lost and cause damage to sensitive parts in the accelerator. By using bent crystals, halo particles can be efficiently extracted from the beam and collected by absorbers further away, reducing the complexity of the system. One major difficulty that aries is that the higher the energy of the particle, the lower the angular acceptance for channeling. Hence, a high precision positioning mechanism with a high angular accuracy is required. The rotational stage (with a range of 20 mrad) is of necessity to be able to track reference trajectories at ramp rates of 100 μrad/s and reject external disturbances to maintain a maximum tracking error of ± 1 μrad.

This project aims to identify the possible control approaches that could be applicable to this problem to achieve the desired performance.

1.3 Prospective challenges

First of all, piezoelectric actuators show strong nonlinear properties such as hysteresis and creep (drift), which have to be compensated for. Moreover, the mechanical flexural structure in combination with the piezo electric characteristics leads to a highly resonant structure. Making it difficult to achieve the desired performance while operating the rotational stage within noisy environments, e.g. LHC, with external disturbances such as ground vibrations.

Furthermore this rotational stage is attached to a linear stage which is composed by a leadscrew, a stepping motor and an axel. The linear movement adds additional perturbation to the rotational stage due to imperfections in the leadscrew and detent torque and stepping nature of the motor.

Finally the system dynamics also show linear position dependence requiring a controller that is robust to such variations.

1.4 Related work

One attempt to achieve the desired performance has already been made. The proposed controller, presented in [3] delivers reasonable performance but does not fulfill the requirements during movement. The authors proposes a PID controller in combination with a pre-filter, and a hysteresis compensator. The controller has shown high disturbance rejection at the first resonance peak as well as good tracking performance.

1.5 Outline

en preliminär problemformulering satt i relation till litteraturbasen

2

Method

This thesis will identify possible control approaches that could be applicable to the rotational stage at CERN in order to meet the performance requirements. First of all, a brief analysis of the already developed controller will be done in order to point out the drawbacks and determine which controller qualities that have to be improved in order to achieved the desired performance during linear movement of the rotational stage. The main work will then consist of investigating different control approaches such as feedforward, iterative or state feedback control. The most promising approaches will be benchmarked in simulations and compared to the existing algorithm. Finally, the most promising alternative will be implemented and tested on the real rotational stage.

2.1 Literature review

Here follows a review of the preliminary literature base that will be used in this thesis. It will most likely be extended with more articles, papers and books throughout the work.

[1] *- Memory characteristics of hysteresis and creep in multi-layer piezoelectric actuators: An experimental analysis*

The aim of this article is to provide an explanation of peculiar features of the PEA response. It presents an experimental characterization of the nonlinear effects i.e. hysteresis and creep in a piezoelectric actuator (PEA). The authors find that both the instantaneous and delayed response of the PEA have hysteric dependence on the applied voltage level. Moreover, they present experimental evidence for that the two observed hysteretic relationships share a common memory structure i.e. they are not truly independent nonlinear phenomenas.

[2]- *On the identification of Hammerstein systems in the presence of an input hysteretic nonlinearity with nonlocal memory: Piezoelectric actuators – an experimental case study*

This paper discusses the identification procedure of the linear dynamic part of piezo based actuators. A Hammerstein structure, consisting of a static (rate independent) hysteresis model with nonlocal memory (the current output does not only depend on the current input voltage but also on its history) and a linear dynamic model, is employed in order to model the hysteretic and dynamic behavior of the actuator. For the identification of the linear part, a careful choice of the driving signal has to be made to avoid modifying the characteristics of the excitation. The authors shows that a choice of a PBRS signal allows the decoupling of the identification of the linear and nonlinear part, since the nonlinear part only transforms the PBRS signal into another PBRS.

[3] *- Controller Design and Verification for a Rotational Piezo-based Actuator for Accurate Positioning Applications in Noisy Environments*

This paper presents the modeling and controller design of a piezo actuated rotational stage operating in a noisy environment at CERN. The authors have adopted a Hammerstein structure, allowing them, in principal, to decouple the nonlinear hysteresis from the linear system dynamics. The extracted linear dynamics was identified as an OE system using several pseudo random binary signals (PBRS) as excitation signals. By adding different voltage biases to the PBRS it was also verified that the operating voltage point influences the identified transfer function (TF). The DC gain and the first resonance frequency and amplitude was affected due to the nonlinear piezo properties.

A 2-DOF controller (feedback and prefilter) and a hysteresis compensator were adopted in order to obtain the desired tracking and disturbance rejection. The proposed controller was designed as a series combination of a PID controller, a lead network and a 4^{th} order notch filter according to the quantitative feedback theorem (QFT). The proposed controller was experimentally tested and showed both disturbance rejection and good tracking capability.

[4] *- A survey of control issues in nanopositioning*

This paper reviews the control-related research in nanopositioning, covering nanopositioning applications, actuators and sensors as well as control challenges. It focuses on piezoelectric actuators discussing both issues in control and different control techniques. Modeling techniques for the nonlinear effects i.e. creep and hysteresis as well as issues such as vibrations and modeling errors are presented in this work. Finally, different control schemes to mitigate the impact from these issues were reviewed such as feedback, forward, iterative and sensor less control.

[5] ***- Piezoelectrics in Positioning, Tutorial on Piezotechnology in Nanopositioning Applications***

This tutorial by Physik Instrumente (PI) gives the reader an overview of the fundamentals of piezoelectricity, piezomechanics and piezo actuators as well as detailed information regarding control approaches, environmental dependencies and design of piezoelectric positioning drives/systems. The electrical, mechanical and thermal behavior of piezoelectric actuators is described by basic equations presented in the paper. Several methods to improve the piezo dynamics are also discussed, such as linearization, signal preshaping and InputShaping® which is a patented real-time feedforward technology.

[6] ***- Design, Modeling and Control of Nanopositioning Systems***

2.2 Timeplan

A timeplan for the thesis will be added here.

3 Result

This section describes future results that could be expected half way through the project.

3.1 Control Approaches

Most of the control approaches should already be identified half way trough the project and most of the literature study shall be finished. All control approaches that at the time have been simulated will be presented with a schematic structure, transfer functions or state space model, a bode plot of the closed loop system and additional plots for illustration of the trajectory tracking capability and the robustness.

3.2 Benchmark tests

Benchmark tests will be carried out on all simulated control approaches and presented here. Comparisons between the new control approaches and the existing algorithm with respect to disturbance rejection, trajectory tracking and bandwidth will be illustrated in plots and tables.

4

Conclusions

Sätt av ett kort kapitel sist i rapporten till att avrunda och föreslå rikningar för framtida utveckling av arbetet.

Appendix

A

definitions

Bibliography

[1] Giustiniani A. Masi A. Biggio M., Butcher M. and Storace M. Memory characteristics of hysteresis and creep in multi-layer piezoelectric actuators: An experimental analysis. *Physica B: Condensed Matter*, 435:40–43, 2014. Cited on page 5.

[2] Giustiniani A. Butcher M. and Masi A. On the identification of hammerstein systems in the presence of an input hysteretic nonlinearity with nonlocal memory: Piezoelectric actuators – an experimental case study. *Physica B: Condensed Matter*, pages 1—-5, 2015. Cited on page 6.

[3] Losito R. Butcher M., Giustiniani A. and Masi A. Controller design and verification for a rotational piezo-based actuator for accurate positioning applications in noisy environments. *Iecon 2015*, 2015. Cited on pages 2 and 6.

[4] Eleftheriou E. Devasia S. and Moheimani R. A survey of control issues in nanopositioning. *IEEE Transactions on Control Systems Technology*, 15(5): 802—-823, 2007. Cited on pages 1 and 6.

[5] Eleftheriou E. Devasia S. and Moheimani R. Piezoelectrics in positioning. tutorial on piezotechnology in nanopositioning applications. *Physik Instrumente (PI) GmbH and Co. KG.*, Retreived in January 2008. URL `http://www.physikinstrumente.com/en/pdf_extra/2009_PI_Piezo_University_Designing_with_Piezo_Actuators_Tutorial.pdf`. Cited on pages 1 and 7.

[6] Fleming A. J. and Leang K. K. *Design, Modeling and Control of Nanopositioning Systems*. Springer International Publishing, first edition, 2014. Cited on page 7.

[7] Website. The ua9 experiment is investigating how crystals could help to steer particle beams in high-energy colliders, Retreived in January 2016. URL `http://home.cern/about/experiments/ua9`. Cited on page 2.

Index