An Evolutionary Approach to Physics-based Modelling of Piezoelectric Actuators

Narges Miri

School of Mechanical Engineering
The University of Adelaide
South Australia 5005

Supervisors:
Dr. Lei Chen
Dr. Morteza Mohammadzaheri

This thesis is submitted in fulfilment of the requirements for the degree of Master of Philosophy on 3rd October 2014

Abstract

The objective of this research is to improve physics-based models of piezoelectric actuators through developing a global parameter identification method for the models and introducing a new high performance model. Piezoelectric actuators produce nano-metre scale displacements making them the dominant actuators in nanopositioning applications. In nanopositioning, the control of actuators' displacement requires highly accurate displacement sensors. The sensors are expensive and difficult, if not impossible, to use. Therefore, the models are employed to estimate the displacement of piezoelectric actuators, using the voltage across them, without any displacement sensors. Accordingly, several mathematical models have been developed to estimate the displacement of piezoelectric actuators. However, due to the nonlinear behaviour of the actuators, the models cannot capture their behaviour precisely. Therefore, developing a model to simulate the nonlinear behaviour of the actuator would constitute an important contribution to the development of high precision sensorless nanopositioning systems. Models can also be used in control system design.

To model piezoelectric actuators, this research utilises physics-based models that have a small number of parameters compared with standard black box models of piezoelectric actuators minimising the computation efforts in real-time applications. In this thesis, the physics-based models are enhanced by dealing with two main diagnosed weaknesses of these models: (1) the lack of a global parameter identification method and, (2) the relatively low accuracy of the models due to their inadequate mathematical structure.

The method for identifying the parameters of the physics-based models is one of the main challenges for these models. In general, the parameters of physics-based models are determined by non-optimal *ad-hoc* methods. Hence, this research adopts a standard, optimal and global (*non-ad-hoc*) method to identify the parameters of the nonlinear models of the piezoelectric actuators.

Another challenge for the physics-based models of piezoelectric actuators is the relatively low accuracy of the models compared with the black box models, partially arising from the rather simple mathematical structure and a small number of parameters of these models. Therefore, improving the model structure will increase the model accuracy. To address this matter, complementary terms/inputs are added to a physics-base model constructing an enhanced structure for the model. The new model doubles the estimation accuracy of the original model and results in accuracies comparable with those of the best reported models of piezoelectric actuators.

The proposed ideas are substantiated to increase the applicability and accuracy of the models of piezoelectric actuators. From the range of physics-based models, the Voigt model is a particular focus for this research. The Voigt model can capture the rate-dependent and nonlinear behaviour of piezoelectric actuators. Furthermore, this model has been reported to be adequate for a broad excitation frequency range (1-1000) *Hz*. However, the proposed ideas are easily extendable to other physics-based models of piezoelectric actuators.

Statement of Originality / Declaration by author

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

I give consent to this copy of my thesis when deposited in the University Library, being made available for loan and photocopying, subject to the provisions of the Copyright Act 1968.

The author acknowledges that copyright of published works contained within this thesis resides with the copyright holder(s) of those works.

I also give permission for the digital version of my thesis to be made available on the web, via the University's digital research repository, the Library catalogue and also through web search engines, unless permission has been granted by the University to restrict access for a period of time.

Signed……………………………Date…………………………

NOTE:

This page is intentionally left blank.

Acknowledgements

It is a great pleasure to acknowledge the many people who have made this thesis possible.

Firstly, I would like to thank my supervisors Dr Lei Chen and Dr Morteza Mohammadzaheri, who have been a supportive supervisory team. Without their advice and feedback, technically and otherwise, I would not have completed my thesis.

I would also like to thank Dr Steven Grainger and Dr Mohsen Bazghaleh for providing experimental data. And, I would like to thank Miss Alison Jane-Hunter and Dr Peter Trudinger who helped with the editing of my thesis.

I am grateful to all the academic faculty and staff at the School of Mechanical Engineering. In particular, they gave me this opportunity to study among Engineers while I have a Science background. I should also express my sincere gratitude to Professors Colin Hansen, Bassam Dally and Associate Professor Anthony Zander, for their friendly conversations and support, especially in my early months in the School of Mechanical Engineering.

I would like to thank all my friends in the School of Mechanical Engineering who have supported me emotionally and scientifically. They made my time pleasant here.

I would like to thank my family members, parents and siblings, who have always encouraged me and believed in me.

NOTE:

This page is intentionally left blank.

Contents

NOTE:

This page is intentionally left blank.

List of Figures:

NOTE:

This page is intentionally left blank.

List of Tables:

NOTE:

This page is intentionally left blank.

Nomenclature

Abbreviations

ANN	Artificial neural network
NARMAX	Nonlinear autoregressive moving average with exogenous inputs
AFM	Atomic force microscope
PZT	Lead zirconate titanate
PI	Parandtl-Ishlinski
sgn	Sign
exp	Exponential
SQP	Sequential quadratic programming
OSP	One step prediction
GA	Genetic algorithm
MAC	Minimum of absolute change
Max	Maximum value
Min	Minimum value
MAX	Maximum of absolute error
MAE	Mean of absolute error

Symbol

E	Electric field
T	Stress vector
S	Strain vector
D	Electrical induction

s^{E}	Mechanical flexibility
ε^{T}	Electrical permittivity
d	Piezoelectric coefficient
B	External magnetic field
$y(t)$	Piezoelectric displacement
$\mu(\alpha', \beta')$	Preisach density function
α', β'	Voltage representations in the Preisach model
$y_{\max}$	Local maximum of the piezoelectric displacement
$y_{\min}$	Local minimum of the piezoelectric displacement
y_{ext}	Local extremum of the piezoelectric displacement
$V_{\max}$	Local maximum of the piezoelectric voltage
$V_{\min}$	Local minimum of the piezoelectric voltage
V_{ext}	Local extremum of the piezoelectric voltage
$H(i)$	Backlash (play) operator
i	Width of the backlash operator
ω	Slope of the backlash operator
r	Half-width of the input voltage
y_{0}	Initial displacement of piezoelectric actuator
j	Number of backlash operators/widths
μ	Friction coefficient
N	Normal force
k	Spring stiffness

b	Spring damping coefficient
F	External force (reaction force)
w_i	Saturation force
g_1, g_2	Hysteresis slopes
α, λ, β	Sigmoid parameters
F_c	Initial applied force
n	Number of elements
A_{th}	Theoretical hysteresis loop areas
A_{hyst}	Experimental hysteresis loop areas
l	Number of estimations
m	Number of bits
p_b	Parameter (gene) value
p_min	Minimum value of each parameter (gene)
p_max	Maximum value of each parameter (gene)
T_1	Internal length of the piezoelectric stack
T_2	External length of the piezoelectric stack
W_1	Internal width of the piezoelectric stack
W_2	External width of the piezoelectric stack
H	Height of the piezoelectric stack
L	Length of the lead wire
t_s	Sampling time
r_y	Output order
θ	Parameter vector

$\varphi(t)$	Regression vector
A	Voltage amplitude
f	Voltage frequency