



An Evolutionary Approach to Physics-based Modelling of Piezoelectric Actuators

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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
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Contents

| | |
|---|-----------|
| Abstract | i |
| Statement of Originality / Declaration by author | iii |
| Acknowledgements | v |
| List of Figures: | xi |
| List of Tables: | xv |
| Nomenclature | xvii |
| 1. Chapter 1 - Introduction | 1 |
| 1.1. Present Models of Piezoelectric Actuators | 2 |
| 1.2. Motivation and Gap Statement | 4 |
| 1.3. Thesis Overview | 5 |
| 1.3.1. Thesis Contribution | 5 |
| 1.3.2. Methodology | 6 |
| 1.3.3. Thesis Structure | 7 |
| 1.4. Publications | 8 |
| 1.4.1. Journal Papers | 8 |
| 1.4.2. Conference Proceedings | 9 |
| 2. Chapter 2 - Piezoelectric Actuators | 11 |
| 2.1. Piezoelectricity | 11 |
| 2.2. Piezoelectric Stack Actuator | 12 |
| 2.3. Challenges to Model Piezoelectric Actuators | 13 |
| 2.4. Summary | 17 |
| 3. Chapter 3 - Physics-based Models of Piezoelectric Actuators | 19 |
| 3.1. Models Analogous with Magnetic Systems | 19 |
| 3.1.1. Preisach Model | 20 |
| 3.1.2. Parandtl-Ishlinski Model | 22 |
| 3.2. Models Analogous with Mechanical Systems | 23 |

| | |
|---|-----------|
| 3.2.1. Maxwell-Slip Model..... | 24 |
| 3.2.2. Duhem Model..... | 26 |
| 3.2.3. Voigt Model..... | 27 |
| 3.3. Common Challenges for the Model Selection and Identification | 28 |
| 3.4. Summary..... | 33 |
| 4. Chapter 4 – Innovative Parameter Identification Method for Physics-based Models | 35 |
| 4.1. Parameter Identification..... | 35 |
| 4.1.1. Approaches for Modelling Error Estimation | 37 |
| 4.1.2. Parameter Identification using Optimisation | 39 |
| 4.1.3. Over-fitting Phenomenon in System Identification..... | 40 |
| 4.2. Solving a Real Problem | 41 |
| 4.2.1. Experimental Setup and Data Gathering | 41 |
| 4.2.2. Modelling: Sampling Time and Initial Condition | 45 |
| 4.3. Simulation Results and Analysis | 47 |
| 4.4. Summary..... | 50 |
| 5. Chapter 5 - Structural Enhancement for Physics-based Models..... | 53 |
| 5.1. Model Structure | 53 |
| 5.1.1. Preisach Model | 53 |
| 5.1.2. Modified Black Box Models | 54 |
| 5.1.3. Enhanced Physics-based Models..... | 55 |
| 5.2. Simulation Results and Analysis | 56 |
| 5.3. Summary..... | 62 |
| 6. Chapter 6 - Conclusions and Future Work | 63 |
| 6.1. Conclusions..... | 63 |
| 6.2. Future Work..... | 64 |
| References | 67 |
| Appendices | 78 |
| A. Black Box Models..... | 78 |

| | |
|--|----|
| A.1. Model Structure..... | 78 |
| A.2. Structure of Black Box Models..... | 78 |
| A.3. Fuzzy Models | 80 |
| B. Actuator Input-Output..... | 81 |
| C. Genetic Algorithms | 91 |
| C.1. Evolution | 91 |
| C.2. Parameter Ranges | 92 |
| D. Genetic Algorithm Code in MATLAB..... | 93 |

NOTE:

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List of Figures:

| | |
|---|----|
| Figure 1.1: A typical piezoelectric actuator in (a) a nanopositioning application (Binnig et al., 1986) and (b) a feedback control system..... | 1 |
| Figure 1.2: A typical black box model..... | 3 |
| Figure 2.1: A typical PZT unit cell (Sirohi and Chopra, 2000)..... | 11 |
| Figure 2.2: (a) Symmetrical and (b) non-symmetrical charge distribution of a material..... | 12 |
| Figure 2.3: A typical piezoelectric stack actuator..... | 13 |
| Figure 2.4: The displacement of a piezoelectric actuator vs voltage for a) a sinusoidal and b) a triangular input voltage at three different excitation frequencies..... | 15 |
| Figure 2.5: A creep pattern for a piezoelectric actuator. A dynamic response region is upon applying an electrical field followed by a creep region (Jung and Gweon, 2000)..... | 16 |
| Figure 3.1: Magnetostrictive materials in (a) no external magnetic field, (b) a strong external magnetic field and c) the removed magnetic field..... | 19 |
| Figure 3.2: Applied voltage to a piezoelectric actuator..... | 21 |
| Figure 3.3: (a) A varying input voltage (V) applied to a piezoelectric actuator and, (b) the corresponding integration area for Eq. (3.1)..... | 21 |
| Figure 3.4: A typical hysteresis operator of the Parandtl-Ishlinski model (Ang et al., 2007)..... | 23 |
| Figure 3.5: (a) A single and (b) multiple elasto-slip element(s) of the Maxwell-Slip model (Vo-Minh et al., 2011)..... | 24 |
| Figure 3.6: A schematic of the Maxwell-Slip model (Vo-Minh et al., 2011)..... | 25 |
| Figure 3.7: A single element of the Voigt model..... | 27 |
| Figure 3.8: Typical first order reversal curves..... | 29 |
| Figure 4.1: Estimation of the model error through (a) One Step Prediction (OSP) and (b) Simulation approaches..... | 38 |
| Figure 4.2: A standard procedure of a genetic algorithm..... | 40 |
| Figure 4.3: An electronic input/output (I/O) board..... | 42 |
| Figure 4.4: A signal amplifier..... | 42 |
| Figure 4.5: Configuration of a multilayer piezoelectric stack (Micromechatronics, 2013)..... | 43 |
| Figure 4.6: Multilayer piezoelectric stacks made by NEC/TOKIN (Micromechatronics, 2013)..... | 43 |
| Figure 4.7: Optical sensor and the basics of its work (PHILTEC, 2013)..... | 44 |
| Figure 4.8: Validation errors for different sampling times. The circle refers to the optimum sampling time..... | 46 |

| | |
|---|----|
| Figure 4.9: MAEs versus iteration for the (a) modelling (OSP approach) and (b) model validation. | 49 |
| Figure 4.10: MAEs versus iteration for the (a) modelling (Simulation approach) and (b) model validation. | 49 |
| Figure 4.11: Real and estimated displacement values of the piezoelectric actuator made through Eq. (4.8) (Parameter tuning by the GA with minimal model error achieved through the (a) OSP and (b) Simulation approaches.) | 50 |
| Figure 5.1: Real and estimated displacement values of the piezoelectric actuator made through Eq. (5.4) (Parameter tuning by the GA with minimal model error achieved through the OSP approach). | 59 |
| Figure 5.2: Real and estimated displacement values of the piezoelectric actuator made by Eq. (5.5) (Parameter tuning by the GA with minimal model error achieved through the OSP approach). | 59 |
| Figure 5.3: Real and estimated displacement values of the piezoelectric actuator made by Eq. (5.3) (Parameter tuning by the GA with minimal model error achieved through the OSP approach). | 60 |
| Figure 5.4: Real and estimated displacement values of the piezoelectric actuator made by Eq. (5.4) (Parameter tuning by the GA with minimal model error achieved through the Simulation approach). | 60 |
| Figure 5.5: Real and estimated displacement values of the piezoelectric actuator made by Eq. (5.5) (Parameter tuning by the GA with minimal model error achieved through the Simulation approach). | 61 |
| Figure 5.6: Real and estimated displacement values of the piezoelectric actuator made by Eq. (5.3) (Parameter tuning by the GA with minimal model error achieved through the Simulation approach). | 61 |
| Figure B.1: Sinusoidal excitation voltage at a frequency of 1 Hz. | 82 |
| Figure B.2: Displacement vs time for the piezoelectric actuator excited through a sinusoidal voltage ($A = \pm 20$ V and $f = 1$ Hz). | 82 |
| Figure B.3: Piezoelectric displacement versus voltage at a frequency of 1 Hz. | 83 |
| Figure B.4: Sinusoidal excitation voltage at a frequency of 10 Hz. | 83 |
| Figure B.5: Displacement vs time for the piezoelectric actuator excited through a sinusoidal voltage ($A = \pm 20$ V and $f = 10$ Hz). | 84 |
| Figure B.6: Piezoelectric displacement versus voltage at a frequency of 10 Hz. | 84 |
| Figure B.7: Sinusoidal excitation voltage at a frequency of 100 Hz. | 85 |

| | |
|---|----|
| Figure B.8: Displacement vs time for the piezoelectric actuator excited through a sinusoidal voltage ($A = \pm 20$ V and $f = 100$ Hz). | 85 |
| Figure B.9: Piezoelectric displacement versus voltage at a frequency of 100 Hz..... | 86 |
| Figure B.10: Triangular excitation voltage at a frequency of 1 Hz..... | 86 |
| Figure B.11: Displacement vs time for the piezoelectric actuator excited through a triangular voltage ($A = \pm 20$ V and $f = 1$ Hz). | 87 |
| Figure B.12: Piezoelectric displacement versus voltage at a frequency of 1 Hz..... | 87 |
| Figure B.13: Triangular excitation voltage at a frequency of 10 Hz..... | 88 |
| Figure B.14: Displacement vs time for the piezoelectric actuator excited through a triangular voltage ($A = \pm 20$ V and $f = 10$ Hz). | 88 |
| Figure B.15: Piezoelectric displacement versus voltage at a frequency of 10 Hz..... | 89 |
| Figure B.16: Triangular excitation voltage at a frequency of 100 Hz..... | 89 |
| Figure B.17: Displacement vs time for the piezoelectric actuator excited through a triangular voltage ($A = \pm 20$ V and $f = 100$ Hz). | 90 |
| Figure B.18: Piezoelectric displacement versus piezoelectric voltage at a frequency of 100 Hz. | 90 |

NOTE:

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List of Tables:

| | |
|--|----|
| Table 3.1: Summary of the key features of physics-based models. | 33 |
| Table 4.1: Standard characteristics of the piezoelectric stack. | 44 |
| Table 4.2: Outer dimension of the piezoelectric stack. Unit: mm, l^* : Length of the lead wire. | 44 |
| Table 4.3: Key physical features of the optical sensor. | 44 |
| Table 4.4: Mean absolute errors (MAEs) of the model simulation for different sampling times. | 46 |
| Table 4.5: Parameter ranges and minimum absolute changes (MACs). | 47 |
| Table 4.6: Identified model parameters by two different approaches. | 48 |
| Table 4.7: Modelling and validation errors for the models made by two different approaches. | 48 |
| Table 4.8: Validation errors for the models made by two different approaches. | 50 |
| Table 5.1: Validation errors for the enhanced black box model. | 55 |
| Table 5.2: Identified parameters for three versions of the new model made by two different approaches. | 57 |
| Table 5.3: Validation errors for three models made by the OSP approach. | 57 |
| Table 5.4: Validation errors for three models made by the Simulation approach. | 57 |
| Table 5.5: Validation errors for the Voigt model made by the two approaches. | 58 |
| Table C.1: Three different computational conditions. | 92 |
| Table C.2: Identified parameters for the model (4.8) considering the conditions of Table C.1. | 92 |

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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 |