Uniform-Electric-Field-Approximation Based Modelling of Longitudinal Piezoelectric Transducers

Yangkun Zhang

The University of Adelaide

School of Mechanical Engineering

The University of Adelaide

Australia

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

July 18, 2016

Abstract

Longitudinal piezoelectric transducers (LPT), which collectively refer to piezoelectric actuators, vibrators, sensors and actuators designed for longitudinal deformations or vibrations, are the most widely used piezoelectric devices. LPT model, which can be used to predict the behavior or performance in time/frequency domain, plays a vital role in the design and optimization of these LPT-based applications. Existing models which can be used for dynamic behavior prediction, are based on the complex electro-mechanical coupled fundamentals of piezoelectricity, which involves a complex position-varying electric field. Therefore, solving these models for the design and optimization of LPT-based applications is very computationally inefficient.

After initial extensive investigations of possible effective simplifications in the complex fundamentals for modeling LPT, it is found that the electric field in LPT could be effectively approximated to be uniform (i.e. electric field is independent of its position) and this approximation could greatly simplify and facilitate the modeling of LPT-based applications. Therefore, the aim of this research is to study the uniform-electric-field approximation in simplifying the analysis, modelling and calculations of LPT for facilitating design and optimization of the LPT-based applications. LPT can, in principle, be divided into d31-mode LPT and d33-mode LPT. Both types are investigated in this thesis work.

The main contributions of this thesis work are presented in 6 chapters, with each based on an individual scientific paper.

Paper 1 presents the rationale behind the uniform-electric-field-approximation for d33-mode LPT together with its scope and limitation. Then, based on the approximation, novel simplified fundamentals of both simple-layer-type and stack-type d33-mode LPT are formulated, which could provide a very simple analytical solution, especially for the stack-type.

To facilitate the modeling of free and loaded vibration of d33-mode LPT in a more straightforward way, a simple equivalent circuit is presented in *Paper 2*. The presented circuit is inspired by the network theory and formulated exactly based on the simplified fundamentals of d33-mode LPT presented in *Paper 1*.

In many LPT-based applications, LPT are joined with other layers, such as backing layers and propagating layers. For the calculations and analysis of a multilayer structure, a transfer matrix method is always used. Therefore, to further facilitate the calculation when LPT are joined with other layers, the simplified fundamentals of LPT in *Paper 1* is wrapped into a transfer matrix form as detailed in *Paper 3*.

When LPT are used in a complex structure, a finite element model is widely applied for computation and analysis. Based on the uniform-electric-field-approximation, two simple equivalent finite element models of LPT are presented in *Paper 4*, which can largely simplify the modeling process and reduce the computational efforts of direct finite element modeling of LPT.

Then, *Paper 5* presents the rationale behind the uniform-electric-field-approximation for d31-mode LPT, which is different in nature to those of d33-mode. Also, an equivalent mixing method is proposed to consider electrode and adhesive layers within d31-mode LPT. The related equivalent circuit and transfer matrix of d31-mode LPT are formulated.

Inspired by d33-mode, *Paper 6* presents simple equivalent finite element models of d31-mode LPT.

Declarations

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, 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 in my name, 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 digital research repository, the Library Search and also through web search engines, unless permission has been granted by the University to restrict access for a period of time.

SIGNED: .... DATE: ....

List of Publications

This thesis is not written in the conventional narrative format but in the publication format as a portfolio of publications either published or submitted for publication by peer-reviewed journals according to the 'Academic Program Rules' of the University of Adelaide. The research outcomes of this thesis have results in the generation of 6 either published or submitted journal papers and 2 refereed conference papers which are listed below:

Journal Papers

Paper 1 Zhang, Y., Lu, T. F., & Al-Sarawi, S. (2015). Formulation of a simple distributed-parameter model of multilayer piezoelectric actuators. *Journal of Intelligent Material Systems and Structures*, 1045389X15595294.

Paper 2 Zhang, Y., Lu, T. F., & Peng, Y. (2015). Three-port equivalent circuit of multi-layer piezoelectric stack. *Sensors and Actuators A: Physical*, 236, 92-97.

Paper 3 Zhang, Y., Lu, T. F., Al-Sarawi, S., Tu, Z. (2016). A Simplified Transfer Matrix of Multi-layer Piezoelectric Stack. *Journal of Intelligent Material Systems and Structures*, 1045389X16651153.

Paper 4 Zhang, Y., & Lu, T. F. (2016). Simple Equivalent Finite Element Models of D33-Mode Multi-layer Piezoelectric Actuator, submitted to *Smart Materials and Structures*

Paper 5 Zhang, Y., Lu, T. F., & GAO, W. (2016). Model D31-mode Longitudinal Piezoelectric Transducers. Submitted to *Sensors and Actuators A: Physical*

Paper 6 Zhang, Y., Lu, T. F., & Al-Sarawi, S. (2016). Simple Equivalent Finite Element Models of D31-Mode Multi-Layer Piezoelectric Actuator. Submitted to *Journal of Intelligent Material Systems and Structures*

Conference Papers

Conference-1 Yangkun Zhang and Tien-Fu Lu 2014, 'Investigation on the Uniform-Electrical-Field Assumption for Modeling multi-layer piezoelectric actuators', *8th Asia International conference on Mathematical Modeling and computer simulation*, 23-25 September, Taipei, Taiwan, page 251-254

Conference-2 Yangkun Zhang and Tien-Fu Lu 2014, 'A Simple Distributed Parameter Analytical Model of Multi-layer Piezoelectric Actuator', *8th Asia International conference on Mathematical Modeling and computer simulation*, 23-25 September, Taipei, Taiwan, page 247-250

Acknowledgements

I would like to take this opportunity to thank a number of people whose support and input was crucial in the completion of my research. First of all, I would like to express my sincere gratitude to my principle supervisor, Dr Tien-Fu Lu, for his infinite patience, constant support, encouragement and advice throughout my PhD journey. This research and thesis would not have been completed without his support. Thanks should also go to my co-supervisor, Dr Said Al-Sarawi, for his constant help in this research and careful revisions and detailed feedbacks in each journal paper.

In addition, I would like to express my gratitude to Dr Yuxing Peng, Mr Jiawei Lu and Mr Yao Wang. They have provided me with tremendous support and given me great encouragement which helped me to go through the hardest period of my research.

Besides, I would also like to thank my PhD colleagues: Hao Huang, Chenxi Li, Boyin Ding, Fantai Meng, Fenglin Chen, Zhen Tu, Yuchi Liang, Da Sun, Shi Zhao, and Sheng Zhang for their guidance and discussion in this research and their joyful company in my university study.

Finally, but foremost, I would like to express my great love and eternal appreciation to my wife, Mrs Lixia Zhou and my parents, Mr Junfu Zhang and Mrs Shumei Yao. Without their never-ending love, encouragement, and support throughout my PhD study, the completion of this research and thesis would have been a much more difficult process.

Table of Contents