

**DESIGN AND DEVELOPMENT OF PZT BASED
MICROPUMP FOR MICROFLUIDIC APPLICATIONS**

Fathima Rehana Munas

148054T

Thesis submitted in fulfillment of the requirements for the degree of Master of
Philosophy

Department of Mechanical Engineering

University of Moratuwa
Sri Lanka

January 2020

DECLARATION

I declare that this is my own work and this thesis does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

Also, I hereby grant to University of Moratuwa the non-exclusive right to reproduce and distribute my dissertation, in whole or in part in print, electronic or other medium. I retain the right to use this content in whole or part in future works (such as articles or books).

Signature

Date

The above candidate has carried out research for the MPhil thesis under my supervision.

Name of the supervisor: Dr. Y.W.R. Amarasinghe

Signature of the supervisor:

Date

ABSTRACT

The present technical context is promptly growing in implementing onsite microfluidic utensils utilized in microfluidics owing to their great demand. The microfluidics mainly involves in implementing minuscule devices to deal with minute volumes of fluids. Manufacturing these microfluidic devices like micropumps is a great challenge and micropumps are very much indispensable to regulate and convey fluid in minute scale.

In this research a PZT based micropump was designed and developed for microfluidic applications. A PZT actuated brass diaphragms and a comprehensive flow arrangement are the important elements of this micropump structure. Basically, the design prominences on a cross junction, engendered by a nozzle jet with a pump chamber and two inlet and an outlet channel respectively. In this sense, the fluid flow rectification is done by nozzle jet feature to expedite the fluid path within the system during every vibration cycle of PZT diaphragm. This micropump device was developed with layer by layer fabrication of polymethyl methacrylate (PMMA) plates using laser cutters and all the layers were squeezed in to attain required structure.

In order to recognize the physiognomies of flow and to verify the experimental outcomes with simulated data, numerical simulation analysis in ANSYS were carried out. In addition, the PZT diaphragms were under taken for eigenfrequency study analysis in COMSOL Multiphysics as well. In this sense, the applied frequency of the piezoelectric diaphragms was varied by using the prescribed control system developed for this device. As per the test results, the maximum flow rate of 31.15 ml/min achieved at the frequency of 100 Hz. In addition, the thin film deposition techniques and the thermo elastic damping analysis on PZT actuators were also analyzed to identify the performance enhancement of this micropump.

Since monitoring pressure and getting response is vital in microfluidic devices, design and simulation of MEMS based piezoresistive pressure sensor has been carried out. According to the piezoresistive structural coupled field analysis, the optimal diaphragm structure was chosen among three kinds of diaphragms considered for this study. Further, the thermo mechanical behavior of piezoresistive pressure sensors have also been considered in this research.

At last, the complete numerical simulation was done for the micropump fluid flow coupled with the designed pressure sensor. According to this analysis, the pressure sensor gives the favorable sensitivity variation over micropump discharge pressure. Hence the developed micropump is not only for a specific application but also worthwhile in a wide range of microfluidic applications.

Keywords: PZT, valveless, micropump, MEMS, Piezoresistive, Pressure Sensor

DEDICATION

This thesis work is dedicated to my family and my teachers. A special feeling of gratitude to my loving parents, who have always loved me unconditionally and whose good examples have taught me to work hard for the things that I aspire to achieve. Also, I am truly thankful to my husband who has been a constant source of support and encouragement during the challenges.

ACKNOWLEDGMENT

I take this great opportunity to express my profound gratitude and deep regards to my research supervisor Dr. Y.W.R. Amarasinghe for his exemplary guidance, monitoring and constant encouragement throughout my research. Without his keen supervision none of this work would have been possible for myself alone.

I consider myself very fortunate for being able to work with such a resourceful individual. I also express my sincere gratitude to my co-supervisors Dr. Van Thanh Dau and Dr. Pubudu Kumarage for their cordial support, valuable information and guidance, which helped me to carryout simulations in this task through various stages. I also would like to remind Prof. Dzung Viet dao and Dr. Van Thanh Dau for their valuable feedbacks and guidance in my publications even they are busy with their schedule.

Moreover, I'm particularly grateful to the Head of the Department of Mechanical Engineering as well as one of the panel members of this research Prof. R.A.R.C. Gopura, for his tremendous support and guidance. Furthermore, I would like to extend my utmost gratefulness to Dr. A.G. Buddhika P. Jayasekara who is the chair of the progress review panel appointed for this research, for his valuable comments and advices given to me throughout this research. I also thankful to Dr. Damith Chathuranga who is the research coordinator of the Department of Mechanical Engineering.

I would like to especially thank to the Final year project students N.H.R.G. Melroy, G.C.B. Abeynayake and H.L. Chathuranga who helped me in the fabrication process. I also thank to the staff of the Mechatronics and MEMS/NEMS laboratory of Department of Mechanical Engineering for providing me the facility required for conduction my research works whenever required.

I especially thank to Mr. Eranga De. Silva, Mr. Isururu Udayange, Mr. Pesan Sampath, Mr. Janaka Basnayake and Mr. Uditha Roshan for their valuable support in the mechatronic laboratory. I also owe my thankfulness to the Head of the Department of Mechanical Engineering, Faculty of Engineering, South Eastern University of Sri Lanka for his great support.

Last but not the least I express my sincere gratitude to everyone who supported me throughout my research work.

Fathima Rehana Munas,
MPhil Postgraduate,
Department of Mechanical Engineering,
University of Moratuwa.

TABLE OF CONTENTS

Declaration.....	i
Abstract.....	ii
Dedication.....	iii
Acknowledgement.....	iv
List of Figures.....	x
List of Tables.....	xvi
List of Abbreviations.....	xvii
1.0 Introduction.....	1
1.1 Aims and Objectives.....	3
1.1.1 Aim.....	3
1.1.2 Objectives.....	3
2.0 Literature Review.....	5
2.1 Micropumps and microfluidic applications.....	5
2.1.1 What is Micropump.....	5
2.1.2 Applications of Micropumps.....	7
2.1.3 Commercial availability of micropumps for microfluidic applications.....	8
2.1.4 Classification of Micropumps.....	9
2.1.5 Design specifications and parameters.....	10
2.1.5.1 Actuator.....	10
2.1.5.2 Valves.....	10
2.1.5.3 Chamber or Reservoir.....	10
2.1.5.4 Nozzle/Diffuser Element.....	10
2.1.5.5 Pumping parameters.....	11
2.1.6 Mechanical Micropumps.....	12
2.1.7 Actuation Principles.....	13
2.1.7.1 Electrostatic actuation.....	13
2.1.7.2 Piezoelectric actuation.....	14
2.1.7.3 Thermo-pneumatic actuation.....	15
2.1.7.4 Electromagnetic actuation.....	16

	2.1.7.5 Shape memory alloy actuation.....	17
	2.1.7.6 Bimetallic actuation.....	18
2.1.8	Dynamic/Non-Mechanical Micropumps.....	18
	2.1.8.1 Hydro dynamic micropumps.....	19
	2.1.8.2 Electro osmotic micropumps.....	19
	2.1.8.3 Electro wetting micropumps.....	20
	2.1.8.4 Bubble-type micropumps.....	21
	2.1.8.5 Electrochemical micropumps.....	21
2.1.9	Material selections and fabrication techniques of the micro pump.....	22
	2.1.9.1 Material selection.....	22
	2.1.9.2 Manufacturing techniques of existing fabricated micropumps.....	23
	2.1.10 Thermo-elastic damping effect in PZT actuators.....	33
2.2	MEMS based Pressure Sensors.....	33
	2.2.1 Applications of MEMS Pressure Sensors.....	34
	2.2.2 Sensing principles and Existing Pressure sensors.....	35
	2.2.3 Available Materials and Fabrication techniques of pressure sensors.....	37
	2.2.4 Thermo-mechanical behavior of pressure sensors.....	39
2.4	Conclusion- Literature Review.....	41
3.0	Design and Simulation of Micropump.....	43
	3.1 Introduction.....	43
	3.2 Design of nozzle jet	44
	3.3 Design and simulation of PZT Actuated diaphragms.....	46
	3.3.1 Effect of Piezoelectric (PZT) actuation in PZT actuators.....	47
	3.4 Design and model development of micropump.....	52
	3.4.1 Design and model setup of single diaphragm micropump.....	53
	3.4.2 Design and model setup of dual	

	diaphragm micropump.....	55
3.4.3	Working principles of micropump.....	56
3.4.4	Simulation analysis of micropump	58
4.0	Fabrication of Micropump.....	63
4.1	Material selection and Laser fabrication.....	63
4.2	Fabrication of single diaphragm micropump	63
4.3	Fabrication of dual diaphragm micropump	65
5.0	Electrical Circuitry and Signal Conditioning.....	68
6.0	Testing and Validation.....	70
7.0	Performance Enhancement of Micropumps.....	77
7.1	Thin film deposition techniques on PZT actuators.....	77
7.2	Thermo Elastic Damping Analysis in PZT Actuators	84
7.2.1	Cooling air flow calculation of PZT actuators.....	90
8.0	Design and Simulation of MEMS based Pressure Sensor.....	91
8.1	Introduction.....	91
8.2	Available kinds of Diaphragms for Pressure Sensors.....	92
8.3	Thin Plate Deflection Theory.....	93
8.3.1	Square type diaphragm.....	94
8.3.2	Circular type diaphragm.....	94
8.3.3	Rectangular type diaphragm.....	95
8.4	Design and simulation of microstructure.....	96
8.4.1	Design of microstructure.....	96
8.4.2	Simulation Analysis of microstructure.....	100
8.5	Design and simulation analysis of sensing elements.....	106
8.6	Sensitivity Enhancement.....	112
8.7	Thermo-mechanical effect in pressure sensors.....	113
8.7.1	Thermal effect on the piezoresistive coefficient.....	113
8.7.2	Thermal effect on the sensitivity.....	114
8.7.3	Thermo-mechanical simulation.....	115
9.0	Numerical Simulation of Micropump Coupled with Pressure Sensor.....	120
9.1	Introduction.....	120

9.2	Simulation analysis of micropump coupled with pressure sensor.....	120
10.0	Discussion.....	123
	Conclusion.....	126
	References.....	128
	Appendix A: Production drawings of micropump.....	136
	Appendix B: Arduino Code of Graphical User Interface.....	138
	Appendix C: Overall design of the signal conditioning circuit.....	140

LIST OF FIGURES

Figure 1	: Proposed design of the Micropump.....	3
Figure 2.1.1 a	: Schematic illustration of a Micropump.....	6
Figure 2.1.1 b	: Photographs of Micropump.....	6
Figure 2.1.2	: Application areas of Micropumps.....	7
Figure 2.1.3	: Micropump produced by Dolomite Company.....	8
Figure 2.1.4	: Classification of micropumps.....	9
Figure 2.1.5.4	: Schematic Diagram of Nozzle/Diffuser element.....	11
Figure 2.1.7.1	: Electrostatic principle of Actuation.....	13
Figure 2.1.7.2	: Piezoelectric principle of Actuation.....	15
Figure 2.1.7.3	: Thermo- pneumatic principle of Actuation.....	16
Figure 2.1.7.4	: Electromagnetic principle of Actuation.....	16
Figure 2.1.7.5	: Schematic illustration of shape memory alloys.....	17
Figure 2.1.7.6	: Schematic diagram of bimetallic Micropump.....	18
Figure 2.1.8.2	: Schematic diagram of Electro-Osmotic Micropump.....	20
Figure 2.1.8.3	: Schematic diagram of Electro Wetting (EW) Micropump.....	20
Figure 2.1.8.4	: Schematic illustration of Bubble type Micropump.....	21
Figure 2.1.8.5	: Schematic illustration of Electrochemical Micropump.....	22
Figure 2.1.9.2 a	: The basic steps of Shape Deposition manufacturing process.....	24
Figure 2.2.3 a	: Sectional view of piezoresistive pressure sensor fabrication with electrochemical technique-sectional view.....	38
Figure 2.2.3 b	: Piezo-resistive pressure sensor made by using Boron doping etch-stop technique- sectional view	38
Figure 2.2.3 c	: Deep Reactive Ion Etching Process.....	38
Figure 3.1	: The 3D model of micropump with significant features.....	43
Figure 3.2 a	: Three dimensional model of nozzle jet.....	44
Figure 3.2 b	: Flat walled diffuser.....	44
Figure 3.2 c	: Conical diffuser.....	45
Figure 3.2 d	: Stability map of a Flat diffuser.....	45
Figure 3.2 e	: Performance map for a typical flat walled diffuser.....	46
Figure 3.3	: PZT actuated membrane.....	47

Figure 3.3.1 a	: Designed model of the PZT actuated diaphragm.....	50
Figure 3.3.1 b	: Meshed model of the PZT actuated diaphragm.....	50
Figure 3.3.1 c	: Deflection analysis of first mode of PZT 5H diaphragm.....	51
Figure 3.3.1 d	: Deflection analysis of fourth mode of PZT 5H diaphragm.....	51
Figure 3.4	: Design of micropumps - two kinds of designs.....	52
Figure 3.4.1 a	: Details of the microfluidic channel.....	53
Figure 3.4.1 b	: The designed model of single diaphragm Micropump - Top view.....	54
Figure 3.4.1 c	: The designed model of single diaphragm Micropump - Bottom view.....	54
Figure 3.4.2 a	: The whole packed model	55
Figure 3.4.2 b	: The exploded view of the model.....	56
Figure 3.4.3 a	: Deformation pattern during the compression stroke	57
Figure 3.4.3 b	: Fluid flow motion during the compression stroke.....	57
Figure 3.4.3 c	: Deformation pattern during the suction stroke	58
Figure 3.4.3 d	: Fluid flow motion during the suction stroke.....	58
Figure 3.4.4 a	: Volumetric plot of velocity profile for single diaphragm micropump.....	60
Figure 3.4.4 b	: Variation of net flow rates with frequency for model 1.....	61
Figure 3.4.4 c	: Volumetric plot of velocity profile for model 2.....	62
Figure 3.4.4 d	: Variation of net flow rates with frequency for model 2.....	62
Figure 4.2 a	: Position of diaphragm with states during suction and compression.....	64
Figure 4.2 b	: Fabricated thin layers of micropump.....	64
Figure 4.2 c	: Single diaphragm micropump.....	65
Figure 4.3 a	: Position of diaphragm with states during suction and compression.....	66
Figure 4.3 b	: Components of the dual diaphragm micropump.....	67
Figure 4.3 c	: Assembled view of fabricated dual diaphragm micropump.....	67
Figure 5.0	: Experimental Layout.....	68
Figure 6.0 a	: Flow rate at 5 s.....	70

Figure 6.0 b	: Flow rate at 10 s.....	70
Figure 6.0 c	: Flow rate at 15 s.....	71
Figure 6.0 d	: Flow rate at 20 s.....	71
Figure 6.0 e	: Flow rate at 25 s.....	71
Figure 6.0 f	: Flow rate at 30 s.....	72
Figure 6.0 g	: Flow rate at 35 s.....	72
Figure 6.0 h	: Flow rate at 40 s.....	72
Figure 6.0 i	: Flow rate at 45 s.....	73
Figure 6.0 j	: Flow rate at 50 s.....	73
Figure 6.0 k	: Flow rate at 55 s.....	73
Figure 6.0 l	: Flow rate at 60 s.....	74
Figure 6.0 m	: Variation of net flow rates with frequency.....	75
Figure 6.0 n	: Variation net flow rates with discharged head at constant frequency.....	76
Figure 7.1 a	: Designed model of the PZT brass diaphragm with thin layer deposition of PMMA	78
Figure 7.1 b	: Designed model of the PZT brass diaphragm with thin layer deposition of PDMS.....	79
Figure 7.1 c	: Deflection analysis of the PZT brass diaphragm with thin film deposition of 100 um PMMA.....	79
Figure 7.1 d	: Von misses stress analysis of the PZT brass diaphragm with thin film deposition of 100 um PMMA.....	80
Figure 7.1 e	: Deflection analysis of the PZT brass diaphragm with thin film deposition of 220 um PMMA.....	80
Figure 7.1 f	: Von misses stress analysis of the PZT brass diaphragm with thin film deposition of 220 um PMMA.....	81
Figure 7.1 g	: Deflection analysis of the PZT brass diaphragm with thin film deposition of 100um PDMS.....	82
Figure 7.1 h	: Von misses stress analysis of the PZT brass diaphragm with thin film deposition of 100um PDMS.....	82
Figure 7.1 i	: Deflection analysis of the PZT brass diaphragm with thin film deposition of 220um PDMS.....	83

Figure 7.1 j	: Von misses stress analysis of the PZT brass diaphragm with thin film deposition of 220um PDMS.....	83
Figure 7.2 a	: Displacement profile of a simple PZT actuator at first mode frequency.....	84
Figure 7.2 b	: Displacement profile of a simple PZT actuator at second mode frequency.....	85
Figure 7.2 c	: Stress profile of a simple PZT actuator at first mode frequency	85
Figure 7.2 d	: Stress profile of a simple PZT actuator at second mode frequency	86
Figure 7.2 e	: Variation of Q factor with mode frequencies for simple PZT actuator at 300 K.....	87
Figure 7.2 f	: Variation of Q factor with mode frequencies for PDMS thin film deposited PZT actuator at 300K.....	87
Figure 7.2 g	: Variation of Q factor with mode frequencies for PMMA thin film deposited PZT actuator at 300K.....	88
Figure 7.2 h	: Variation of heat generation and heat dissipation with temperature for PZT actuator at first mode frequency	88
Figure 7.2 i	: Variation of heat generation and heat dissipation with temperature for PDMS thin film deposited PZT actuator at first mode.....	89
Figure 7.2 j	: Variation of heat generation and heat dissipation with temperature for PMMA thin film deposited PZT actuator at first mode.....	89
Figure 8.1 a	: MEMS based pressure sensor – 3D model.....	91
Figure 8.1 b	: Design concept of MEMS based piezoresistive pressure sensor.....	91
Figure 8.2 a	: Circular flat type diaphragm.. ..	92
Figure 8.2 b	: Square flat type diaphragm.. ..	93
Figure 8.2 c	: Sculptured type diaphragm	93
Figure 8.3.1	: Square type diaphragm.....	94

Figure 8.3.2	: Circular type diaphragm.....	94
Figure 8.3.3	: Rectangular type diaphragm.....	95
Figure 8.4.1 a	: Three dimensional mesh plot for square shaped diaphragm.....	97
Figure 8.4.1 b	: Three dimensional mesh plot for circular shaped diaphragm.....	97
Figure 8.4.1 c	: Three dimensional mesh plot for cross sectional beam shaped diaphragm.....	98
Figure 8.4.1 d	: Proposed solid model for square type diaphragm.....	98
Figure 8.4.1 e	: Proposed solid model for circular type diaphragm	99
Figure 8.4.1 f	: Proposed solid models for cross sectional beam type diaphragm	99
Figure 8.4.2 a	: Deflection and stress profiles of square diaphragm.....	100
Figure 8.4.2 b	: Stress profile of square diaphragm.....	101
Figure 8.4.2 c	: Deflection profile of circular diaphragm.....	101
Figure 8.4.2 d	: Stress profiles of circular diaphragm.....	102
Figure 8.4.2 e	: Deflection profile of cross sectional beam diaphragm.....	102
Figure 8.4.2 f	: Stress profiles of cross sectional beam diaphragm.....	103
Figure 8.4.2 g	: Deflection variation with pressure.....	103
Figure 8.4.2 h	: Stress variation with pressure.....	104
Figure 8.4.2 i	: First Mode of Frequency of Modal Analysis.....	105
Figure 8.4.2 j	: Second Mode of Frequency of Modal Analysis.....	105
Figure 8.4.2 k	: Third Mode of Frequency of Modal Analysis.....	105
Figure 8.4.2 l	: Sixth Mode of Frequency of Modal Analysis.....	106
Figure 8.5 a	: Operation principles of a piezoresistive pressure sensor.....	106
Figure 8.5 b	: Arrangement of piezoresistive elements-Plan view.....	108
Figure 8.5 c	: Wheatstone bridge circuit illustration.....	108
Figure 8.5 d	: Piezoresistive pressure sensor- Designed model.....	110
Figure 8.5 e	: Piezoresistive pressure sensor- Meshed model.....	110
Figure 8.5 f	: Displacement Profiles of pressure sensor.....	111
Figure 8.5 g	: Stress Profiles of pressure sensor.....	111
Figure 8.6	: Variation of sensitivity with applied pressure.....	113

Figure 8.7.1	: Variation of Piezoresistive coefficient with temperature and doping Concentration.....	114
Figure 8.7.2	: Variation of Sensitivity with temperature and doping concentration.....	115
Figure 8.7.3 a	: Variation of central deflection of the membrane with temperature.....	116
Figure 8.7.3 b	: Normal stress of piezo-resistive pressure sensor at 100 kPa and 300K.....	117
Figure 8.7.3 c	: Shear stress of piezo-resistive pressure sensor at 100 kPa and 300K.....	117
Figure 8.7.3 d	: Variation of sensitivity with pressure at different temperatures.....	118
Figure 8.7.3 e	: Variation of output voltage with doping concentration at different temperatures.....	118
Figure 8.7.3 f	: Temperature variation due to ohmic heating.....	119
Figure 9.1	: Entire Theoretical model- Micropump coupled with pressure sensor.....	120
Figure 9.2 a	: Deflection contours of designed pressure sensor.....	121
Figure 9.2 b	: Stress contours of designed pressure sensor.....	121
Figure 9.2 c	: Variation of sensitivity with discharge pressure.....	122

LIST OF TABLES

Table 2.1.9	: Details of the developed micropump.....	25
Table 2.2.2	: Developed sensors incorporated with various kinds of sensing principles.....	36
Table 2.2.4	: The Fitting Coefficients of Ritcher Model.....	41
Table 3.2	: Three kind of nozzle parameters.....	46
Table 3.3.1	: Dimensions of the diaphragm and the material properties of brass.....	49
Table 3.4.4 a	: Simulation results of net flow rates with frequency for model 1..	60
Table 3.4.4 b	: Simulation results of net flow rates with frequency for model 2.	62
Table 6.0 a	: Collected data for different frequency at 0 mm discharged head.....	74
Table 6.0 b	: Experimental results for the average net flow rate and the frequency.....	74
Table 6.0 c	: Data sets for different discharged head at 50Hz	75
Table 6.0 d	: Calculated experimental flow rates at different discharged head.....	76
Table 7.2.1	: The required cooling air flow.....	90
Table 8.3.3	: Coefficients for supreme stress and deflection in Rectangular Plate.....	96
Table 8.4.1	: Proposed parameters of respective diaphragms.....	98
Table 8.4.2	: Material properties of respective diaphragms.....	100
Table 8.5 a	: Distinctive parameters for Piezoresistive Coefficients of Lightly doped Si	107
Table 8.5 b	: Proposed designed Factors of Piezoresistive Pressure Sensor...	109
Table 8.6	: Variation of output voltage and sensitivity with pressure.....	112
Table 9.2 a	: Variation of output voltage and sensitivity with discharge pressure.....	122

LIST OF ABBREVIATIONS

Abbreviation	Description
DRIE	Deep Reactive Ion Etching
EHD	Electro Hydro Dynamic
EO	Electro Osmotic
EW	Electro Wetting
FEM	Finite Element Method
FI	Fluid Inertia
ICPF	Ion Conductive Polymer Films
ITO	Indium Tin Oxide
KOH	Potassium Hydroxide
LOC	Lab On a Chip
MEMS	Micro Electro Mechanical System
MHD	Magneto Hydro Dynamic
μ TAS	Micro Total Analysis System
PCB	Printed Circuit Board
PDMS	Poly Di-Methyl Siloxane
PEEK	Polyether Ether Ketone
PGA	Polyglycolide/ Polyglycolic Acid
PLA	Polylactide/ Polylactic Acid
PMMA	Poly methyl methacrylate
POCT	Point Of Care Testing
PZT	Lead Zirconate Titanate
SDM	Shape Deposition Manufacturing

Abbreviation	Description
SFF	Solid Free Form Fabrication
SL	Stereo Lithography
SMA	Shape Memory Alloys
SOI	Silicon On Insulation