

# **Modelling and Analysis of Wirelessly Interrogated SAW based Micropumps for Drug Delivery Applications**

by

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# Abstract

Many types of life threatening global health problems such as cardiovascular diseases, cancer, and diabetes have placed human life at high risk. These critical health problems may be eliminated and/or controlled with effective early diagnostic and/or targeted treatment methodologies. Conventional drug delivery methods such as oral tablets or injections consist of various limitations. Among them, the problem with variable absorption profiles and need of frequent dosing are yet to be successfully addressed. Therefore conventional methods are not effective for delivering the drug within their therapeutic range. The implementation of targeted micro drug delivery methods is recognised as a critical solution space for twenty first century healthcare.

Micro Electromechanical Systems (MEMS) based typical micropump is a fundamental part of a drug delivery system which provides the actuation source to effectively transfer an accurate amount of fluid/drug to a targeted location. However, the lack of availability of accurate and easy to use, implantable and low-powered micropumps has been identified as a significant problem. Furthermore, the ease of control of implantable biological devices would be greatly improved by incorporation of wireless and secure actuator mechanism with no battery attached with the device. Therefore, in this thesis, several significant contributions to address the above highlighted issues are presented and discussed.

In this thesis, various types of actuation and micropump mechanisms were reviewed; in addition to investigating how Surface Acoustic Wave (SAW) devices can be used for secure, wireless and batteryless actuation. Consequently, SAW based novel transcutaneous interrogation mechanism was proposed for low-powered electrostatic actuations, without the need for active electronics to meet the biocompatibility requirements. A SAW correlator was used for the secure interrogation, where the device responds only to a uniquely coded RF signal, which has to be matched with the code implanted in the SAW correlator. The proposed micro actuation mechanism was demonstrated by utilising a Finite Element Model (FEM). This allowed the investigation of this device performance using a sophisticated computational numerical method. A new theoretical analysis was also developed to derive both electric potential and electrostatic force equations for SAW based microactuators. Then the Rayleigh-Ritz method

based theoretical model was developed to validate the FEM results. Based on these results the SAW based low-powered actuator is able to achieve displacements up to  $3\ \mu\text{m}$  at low operating voltages.

Once the proposed mechanism was verified both analytically and using FEM, the modelling was then extended to analyse the performance of SAW based microdiaphragms, as a critical performance dictator for the diaphragm part of the micropumps. Several new methods were developed and modelled to overcome the existing drawbacks in flat microdiaphragms, such as the incorporation of highly effective corrugated profiles, and effective use of flexible materials. As a result a number of these corrugation profiles were examined using FEA. As a result it is demonstrated that the proposed design approaches have substantially enhanced microdiaphragm performance, compared to a flat diaphragm.

As much as the effectiveness of microdiaphragms, the flow rectification mechanism also dictates a critical role in micropumps. In this research, the proposed micropump was designed to be valveless for simplicity and ease of fabrication, and used diffuser elements for flow rectification. However, most of the existing computational analyses of diffusers are mainly based on 2D or simplified 3D models. Hence, the relationship between diffuser parameters, Reynolds number, and the diffuser performance at microscale, are not well established. Therefore, FEM based Computational Fluid Dynamic (CFD) was successfully utilised to analyse flat-walled diffuser elements. These analyses provide a qualitative and quantitative relationship between the diffuser efficiency and Reynolds numbers for laminar flow.

Building on the developed actuation mechanism and various corrugated micro diaphragms, and diffuser models, an integrated device analysis are presented. This includes a full 3D model of the SAW based electrostatically actuated, diffuser micropump, and complex microfluidic behaviour of the micropump was analysed. A strong emphasis was given in utilising CFD to analyse the Fluid–Solid Interaction (FSI) phenomena of the micropump and the overall pumping effect was successfully demonstrated. The knowledge and new contributions made in this thesis in modelling, simulation, and analysis of implantable drug delivery micropumps, will be able to effectively utilise in a range of fields such as advanced computational numerical modelling of Bio–MEMS, secure transcutaneous communication, and implantable drug delivery systems and other biomedical applications.

# Statement of Originality

This work contains no material that 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 written by another person, except where due reference has been made in the text.

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Signed

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Date



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*Don W. Dissanayake*

March 2010

# Conventions

1. **Formatting:** This thesis is typeset using the  $\text{\LaTeX}$ 2e software. WinEdt build 5.4 was used as an effective interface to  $\text{\LaTeX}$ . Plots and images were generated using Matlab 7.0 (Mathworks Inc.) and MS Excel 2007.
2. **Spelling:** Australian English spelling is adopted, as defined by the Macquarie English Dictionary (Delbridge 2001).
3. **Referencing:** Harvard style is used for referencing and citation in this thesis.





# Awards

## Student Excellence Awards

**State Finalist in the 2009 AusBiotech–GSK Student Excellence Awards, Australia, for outstanding research project.**

**Presentation Title:** Wireless micropump for implantable biomedical applications.

**Competition:** 2009 AusBiotech–GST Student Excellent Awards, Australia.

## Best Presentation Award

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**Presentation Title:** Corrugated micro–diaphragm analysis for low-powered and wireless bio–MEMS.

**Authors:** Don W. Dissanayake, Said Al–Sarawi & Derek Abbott.

**Conference:** 3rd International Conference on Sensing Technology (ICST 2008), Taiwan, 30th Nov–3th Dec 2008.

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# Publications

## Book Chapters

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- DISSANAYAKE-D. W., AL-SARAWI-S. F., AND ABBOTT-D. (2009). *Recent Advances in Sensing Technology*, Lecture Notes in Electrical Engineering, Springer-Verlag, chapter Wireless interrogation of a micropump and analysis of corrugated micro-diaphragms, pp. 139–151, In Press.
- DISSANAYAKE-D. W., AL-SARAWI-S. F., AND ABBOTT-D. (2008). *Smart Sensors and Sensing Technology*, Vol. 20 of *Lecture Notes in Electrical Engineering*, Springer-Verlag, chapter Electrostatic micro actuator design using surface acoustic wave devices, pp. 139–151.

## Journals

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- DISSANAYAKE-D. W., AL-SARAWI-S., LU-T.-F., AND ABBOTT-D. (2009). Finite element modelling of SAW device based corrugated micro-diaphragms, *Smart Materials and Structures*, **18**(9), pp. 095030: 1–11.

## Conferences (Full Paper)

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- DISSANAYAKE-D. W., AL-SARAWI-S., AND ABBOTT-D. (2009). Advanced modeling and simulation of wirelessly interrogated valve-less microfluidic devices, *Proc. of 2009 IEEE Regional Symp. on Micro and Nano Electronics*, pp. 332–336.
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DISSANAYAKE-D. W., AL-SARAWI-S., AND ABBOTT-D. (2007). Surface acoustic wave device based electrostatic actuator for microfluidic applications, *Proc. of 2nd International Conference on Sensing Technology*, pp. 381–386.

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DISSANAYAKE-D. W., TIKKA-A. C., AL-SARAWI-S.(2006). Use of ANSYS in design and analysis of piezoelectrically actuated microvalves for biomedical applications, *Proc. of ANSYS Australasian User Conference 2006*.

## News Articles

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DISSANAYAKE-D. W., AND AL-SARAWI-S. F. (2007). Designing remotely activated microvalves for biomedical applications. SPIE news letter, <http://spie.org/x14241.xml>.

# List of Symbols

Notation	Description
$2\theta$	Diverging diffuser angle
$A$	Effective plate area
$AR$	Area ratio
$A_1$	Cross section of the inlet of the diffuser
$A_2$	Cross section of the outlet of the diffuser
$A_L$	Laplace coefficient
$A_e$	Cross section of the exit of the outlet duct
$A_i$	Cross section of the entrance of the inlet duct
$B_L$	Laplace coefficient
$C_p$	Pressure recovery coefficient
$C_+$	Correlated positive signal
$D$	Electric flux density
$E$	Electric field intensity
$E_{act}$	Total energy of the actuator
$E_{dia}$	Total energy of the microdiaphragm
$H$	Corrugation height
$I$	Moment of inertia
$K_p$	Actuator displacement coefficient
$K_D$	Microdiaphragm displacement coefficient
$K_d$	Total pressure loss coefficient in diffuser direction
$K_n$	Total pressure loss coefficient in nozzle direction
$L$	Corrugation wavelength
$N$	Number of corrugation wavelengths
$N_p$	Number of IDT finger pairs
$N_s$	Divisions per finger gap
$Q$	Flow rate
$Q(t)$	Instantaneous volume averaged flow rate
$Q_d$	Flow rate in diffuser direction
$Q_n$	Flow rate in nozzle direction
$Q_{avg}$	Average flow rate

Notation	Description
$T$	Mechanical stress
$V$	Fluid velocity vector
$V_{gap}$	Electric potential at IDT gap
$V_+$	Electric potential at positive finger
$V_-$	Electric potential at negative finger
$V_{in}$	Input voltage
$W_1$	Diffuser neck width
$W_D$	Instantaneous microdiaphragm deflection
$W_P$	Instantaneous plate deflection
$X_l$	Direction along corrugations
$X_w$	Direction across corrugations
$\Omega$	Electric potential at IDT finger gap
$\Phi$	Electric potential
$\Psi$	Electric potential at positive finger
$\alpha$	Kinetic–energy correction factor
$\alpha_j^m$	Linear coefficients of the plane waves
$\eta$	Diffuser efficiency
$\lambda$	Wavelength
$\mathbb{D}$	Bending stiffness
$\mathbb{E}$	Modulus of elasticity
$L$	Diffuser length
$\mu$	Viscosity
$\nu$	Poisson ratio
$\bar{v}$	Volume–averaged velocity
$\rho$	Density of piezoelectric substrate
$\rho_D$	Density of the microdiaphragm
$i$	Standard imaginary unit $=\sqrt{-1}$
$\epsilon_0$	Permittivity of air
$b^m$	Decaying constant
$c_{ijkl}$	Stiffness tensor
$e_{ijk}$	Piezoelectric coupling tensor
$f_{RF}$	trigger frequency
$f_{SAW}$	SAW frequency
$f_l$	IDT finger length

Notation	Description
$f_w$	IDT finger width
$g$	Gravitational acceleration
$g_{(+)}$	Positive square wave
$h$	Air-gap height
$k$	Wave vector
$l$	largest characteristic dimension
$p$	Hydrostatic pressure across the cross-section
$p_c$	Hydrostatic pressures in the chamber
$p_o$	Hydrostatic pressures in the inlet/outlet
$u$	Mechanical displacement
$u_a$	Axial velocity across diffuser cross section
$v$	Phase velocity
$F_{(+)}$	Electrostatic force from positive IDT finger
$F_{(-)}$	Electrostatic force from negative IDT finger
$F_{(tot)}$	Total electrostatic force
$F_{(\lambda)}$	Electrostatic force per wavelength
$\Phi_L$	Laplace electric potential
$\eta_{rec}$	Flow rectification efficiency
$\nabla^4$	double Laplacian operator
$\bar{v}_1$	Volume-averaged velocity at diffuser inlet
$\bar{v}_2$	Volume-averaged velocity at diffuser outlet
$\rho_L$	Fluid density
$\epsilon_{ij}$	Permittivity
$t_D$	Corrugation thickness





# Abbreviations

KNbO <sub>3</sub>	Potassium Niobate	53
LiTaO <sub>3</sub>	Lithium Tantalate	53
Pb <sub>2</sub> KNb <sub>5</sub> O <sub>15</sub>	Lead Potassium Niobate	53
Si <sub>3</sub> N <sub>4</sub>	Silicon Nitride	52
2D	Two Dimensional	10, 38
3D	Three Dimensional	7
ASI	Air–Structure Interface	147
BEM	Boundary Element Method	6
CAD	Computer Aided Design	4
CAM	Computer Aided Modelling	4
CFD	Computational Fluid Dynamics	5, 126
CRPS	Complex Regional Pain Syndrome	4
DC	Direct Current	148
DoF	Degree–of–Freedom	75
EHD	Electrohydrodynamic	16, 27
EO	Electroosmotic	16
EO	electroosmotic	27
EW	Electrowetting	16
EW	electrowetting	30
FDM	Finite Difference Method	6
FEA	Finite Element Analysis	5
FEM	Finite Element Modelling	5
FPW	Flexural Planar Wave	16, 32
FSI	Fluid–Structure Interaction	6
FVM	Finite Volume Method	6

## Abbreviations

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IC	Integrated Circuit	4
ICPF	Ionic Conductive Polymer Film	16, 24
IDT	Inter Digital Transducers	32, 40
LoC	Lab-on-a-Chip	14
MEMS	Micro Electro Mechanical Systems	1
MHD	Magnetohydrodynamic	16, 25
MnD	Mid-node Displacement	100
PCB	Printed Circuit Board	110
PCR	Polymerase chain reaction	14
PVMD	Percentage Variation in Mid-node Displacement	100
PZT	Lead Zirconate Titanate	19
RF	Radio Frequency	8
RFID	Radio Frequency Identification Device	87
SAW	Surface Acoustic Wave	8, 40
Si	Silicon	52
SMA	Shape Memory Alloy	16, 22

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