Development of Hybrid GA-PSO for Optimal Design of Valveless Micropump in Biomedical Application

by

Aida Fatehah Binti Mohd Shukur

(1130110666)

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LIST OF ABBREVIATIONS

µTAS	Micro Total Analysis Systems
3D	Three - Dimensional
ABC	Artificial Bee Colony
ACO	Ant Colony Optimization
AFSA	Artificial Fish Swarm Algorithm
AI	Artificial Intelligence
ANN	Artificial Neural Network
CFD	Computational Fluid Dynamic
CS	Cuckoo Search
DDS	Drug Delivery System
DE	Differential Evolution
DRIE	Deep Reactive Ion Etching
EHD	Electrohydrodynamic
FA	Firefly Algorithm
FEA	Finite Element Analysis
GA	Genetic Algorithm
GADO	Genetic Algorithm for Design Optimization
GAMA	Genetic Algorithm for Model Adaptation
HPSO-GA	Hybrid PSO and GA
HRA	Harmonic Response Analysis
ICPF	Ionic Conductive Polymer Film
IDT	Interdigitated Transducers
LCD	Liquid Crystal Display
LIPCAs	Lightweight Piezo - Composite Actuators
LOC	Lab-On-A-Chip

MEMS	Micro-Electro-Mechanical Systems
MHD	Magnetohydrodynamic
NSGA-II	Non-Dominated Sorted GA
PDMS	Poly-Dimethylsiloxane
PSO	Particle Swarm Optimization
PZT	Piezoelectric Zirconate Titanate
QoS	Quality-of-Service
SMA	Shape Memory Alloy
TDD	Transdermal Drug Delivery
TiNi	Titanium/Nickel

LIST OF SYMBOLS

A	Narrowest cross-section area
c_1	Constant factors
c_2	Constant factors
d	Diffuser
D	Throat width
E	Young’s Modulus
$F1$	Fitness function for total deformation
$F2$	Fitness function for strain energy
$F3$	Fitness function for equivalent stress
$F4$	Fitness function for resonant frequency
$F5$	Fitness function for net flow rate
$F6$	Fitness function for velocity
F_m	Fitness value for the specification m
$Fm_{average}$	Average value of specification m
F_{tot}	Total fitness value
g_{best}	Best global value
$ITER$	Current iteration
$iter_{max}$	Maximum iteration
L	Length of diffuser/nozzle element
m	Number of inputs
n	Nozzle
P	Distributed pressure
p_{best}	Best position in the current population
P_m	Mutation probability
pos	Particle position

pos^i_k	Position of particle *i* in the dimensional search space at *k* iteration
P_x	Crossover probability
Q	Flow rate
$Q_{d/n}$	Flow rate at diffuser/nozzle element
Q_{net}	Net flow rate of micropump
R	Radius of the diaphragm
$rand$	Randomly generated value
t	Diaphragm thickness
t_c	Pumping chamber thickness
V	Fluid velocity
v	Material Poisson's ratio
V_0	Dead volume
vel	Velocity of particle
vel^i_k	Velocity of particle *i* in the dimensional search space at *k* iteration
w	Inertia weight
W_m	Weight for specification *m*
w_{max}	Maximum value of weight
w_{min}	Minimum value of weight
y_{max}	Diaphragm deformation
α	Penalty value
ΔP	Pressure drop
ΔV	Stroke volume
ε	Compression ratio
η	Efficiency ratio
θ	Opening angle for the diffuser/nozzle element
ξ	Pressure loss coefficient
ρ	Fluid density

Pembangunan Hybrid GA-PSO untuk Reka Bentuk Pam Mikro Tanpa Injap yang Optimum didalam Aplikasi Bioperubatan

ABSTRAK

Pam mikro adalah salah satu komponen yang paling penting didalam bendalir mikro dan sistem mikroelektromekanikal (MEMS) kerana ia mempunyai kebolehan untuk mengangkut bendalir dalam skala mikro dan dapat mengawal kadar aliran dengan tepat dan cekap. Pelbagai reka bentuk dan pendekatan telah dicadangkan untuk membangunkan pam mikro yang mempunyai prestasi yang tinggi. Tesis ini menunjukkan kaedah pengoptimuman untuk pam mikro tanpa injap dengan menggunakan perlaksanaan pendekatan kepintaran tiruan (AI). Pam mikro tanpa injap ini direka bentuk dengan sebuah diafragma, ruangan pengepaman dan elemen penyebaran/penyedutan berfungsi sebagai saluran masuk dan saluran keluar dengan dimensi keseluruhan adalah $5 \times 1.75 \times 5$ mm^3. Perlaksanaan struktur pengoptimuman pam mikro tanpa injap adalah penting untuk menentukan kadar aliran bersih yang maksimum yang boleh dihasilkan oleh pam mikro dengan penggunaan kuasa yang rendah. Bagi menentukan prestasi reka bentuk pam mikro, jumlah perubahan, ketegangan tenaga, jumlah tekanan, frekuensi resonasi untuk diafragma, halaju bendalir dan kadar aliran pam mikro dikaji. Tekanan belakang yang optimum untuk diafragma pam mikro tanpa injap diperolehi memalui hasil penilaian. Pengoptimuman dilakukan untuk memaksimumkan jumlah perubahan, halaju, kadar aliran bersih dan meminimumkan ketegangan tenaga, jumlah tekanan dan frekuensi resonasi pam mikro. Bagi menilai prestasi pam mikro untuk aplikasi perubatan, fungsi kesesuaian dibentuk untuk menilai pembolehubah reka bentuk struktur pam mikro. Didalam menggabungkan alat pengoptimum dengan perisian elemen analysis terhad (FEA) iaitu ANSYS Workbench, simulasi dan model pengoptimuman boleh dibina untuk mencari parameter reka bentuk pam mikro yang paling optimum. Pam mikro tanpa injap yang ditunjukkan dioptimumkan dengan tiga kaedah pengoptimuman yang berbeza iaitu algoritma genetik (GA), pengoptimuman sekumpulan zarah (PSO) dan kacukan/hibrid PSO dengan GA (dinotasikan sebagai HPSO-GA). Hasil simulasi yang diperolehi di bandingkan dan dikaji untuk ketiga-tiga cara pengoptimuman. Dari kajian yang dijalankan, Hasil simulasi menunjukkan bahawa HPSO-GA yang dicadangkan memberikan penyelesaian yang lebih baik untuk prestasi pam mikro. Keputusan yang diperolehi melalui model yang dibangunkan daripada pengoptimuman HPSO-GA menyatakan bahawa jumlah perubahan maksimum diafragma adalah 8.4797 µm dengan 8 kPa tekanan penggerakkan dan kadar aliran bersih yang optimum adalah 3.89 mL/min dengan halaju 4.796 m/s.

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ABSTRACT

Micropumps are one of the most important components of microfluidic and microelectromechanical system (MEMS) because of the ability to transport fluids in microscale and have the control of the flow rate in an accurate and efficient manner. Various designs and approaches are suggested in order to develop a high performance micropump. This thesis presents the optimization method of valveless micropump utilizing the implementation of artificial intelligence (AI) approaches. The valveless micropump is designed with a diaphragm, pumping chamber and diffuser/nozzle elements functions as inlet and outlet with the outer dimension of 5 × 1.75 × 5 mm^3. The implementation of structure optimization of valveless micropump is important in order to determine the maximum net flow rate that can be generated by the micropump with low power consumption. In order to determine the performance of the micropump, the total deformation, strain energy, equivalent stress, resonant frequency for diaphragm, fluid velocity and net flow rate of the micropump are investigated. Optimum back pressure for the diaphragm of valveless micropump was obtained through the result assessment. Optimization is done to maximize the total deformation, velocity, net flow rate and minimize the strain energy, equivalent stress and resonant frequency of the micropump. In order to evaluate the performance of the micropumps for medical application, a fitness function is constructed to evaluate the design variables of micropump structure. By executing optimization tools in conjunction with finite element analysis (FEA) software ANSYS workbench, the simulation and optimization model is able to find out the optimum micropump design parameters. The presented valveless micropumps are optimized in three deferent optimization methods which are genetic algorithm (GA), particle swarm optimization (PSO) and hybrid PSO with GA (denoted as HPSO-GA). Simulation results obtained are compared and investigated for the three optimization methods. From the research, simulation results show that the proposed HPSO-GA provide better solution for micropump performance. Results obtained through the developed model of HPSO-GA optimization stated that the maximum total deformation of the diaphragm is 8.4797 µm with 8 kPa actuation pressure and optimum net flow rate is 3.89 mL/min with velocity of 4.796 m/s.

CHAPTER 1

INTRODUCTION

1.1 Overview of Micropumps

Over the years, development of miniaturized microelectromechanical system (MEMS) devices becomes essential and critical issues to microfluidics applications. Due to the size miniaturization, microfluidics devices have the ability to develop unique transport properties and provide the capability of parallel processing and high throughput. The fields of microfluidics expand with the development of MEMS devices and its application including in lab-on-a-chip (LOC), micro total analysis systems (µTAS), chemical analysis systems, bio-MEMS, medical application and other micro devices (Ashraf, Tayyaba & Afzulpurkar, 2011; Laser & Santiago, 2004; Nguyen, Huang & Chuan, 2002; Yamahata et al., 2005). Advantages of microfluidics in MEMS are very small sizes, low power consumption, high precision, better performance, lower costs, disposability and can be integrated with electronics devices.

Recently, investigations into methods of using microfluidics and MEMS application for medical application and drug delivery systems (DDS) have been expanded (Nuxoll, 2013; Zhang & Nagrath, 2013). MEMS applications are utilized in medical applications and DDS to design the devices and instruments for medical used such as microreservoir, microactuator, microneedle, microvalve, and micropump. In contrast to other microfluidics devices, micropump is a component that has been designed according to its application and requirement such as for microelectronic cooling, micro-space exploration, inkjet printers, chemical injection and especially in medical applications.

Specifically, micropumps are the most important element of MEMS and microfluidics component because of its ability to transport fluids in microscale and to control the flow rate in an accurate and efficient manner. Due to its important role in many microfluidics systems, the outcomes from the constantly building MEMS technology upon microstructures supplies as well as manufacturing systems tend to move to the investigation on micropumps (Anagnostopoulos & Mathioulakis, 2005). The most valuable features of micropumps are miniature of sizes and high precision in controlling fluid have made them very useful in chemotherapy, insulin delivery for diabetic patient and drug dosing for cancer patient (Smits, 1990). Development of micropumps becomes more important due to medical demands in order to transport drug and insulin in micro or nano dosage. In medical application, micropumps are applied to construct DDS that enable enhanced control over the delivery of therapeutic agents (Arora, Prausnitz & Mitragotri, 2008; Martanto et al., 2004; Mousoulis, Ochoa, Papageorgiou & Ziaie, 2011; Zengerle & Richter, 1992). Micropumps have been designed with various types of actuator mechanism used as a device for control on mechanical movement according to the micropump’s application. Generally, micropumps can be developed by using several actuation methods such as electrostatic, piezoelectric, electromagnetic, pneumatic, thermopneumatic, bimetallic and shape memory alloy (SMA) actuation (Nisar, Afzulpurkar, Mahaisavariya & Tuantranont, 2008).

The researches on micropumps began since 1970s whereas MEMS-based micropumps have been developed in 1990s (Ashraf, Tayyaba & Afzulpurkar, 2011;

Olsson, 1998; Woias, 2005). Among the earliest development of micropumps was proposed by Thomas & Bessman (1975) in 1975. Thomas & Bessman (1975) used the micropump for implantation into human body. The micropump was actuated by using piezoelectric disc benders and consists of solenoid valve connected to variable pumping chambers. In 1978, Spencer et al. (1978) proposed cylindrical micropump actuated by piezoelectric stainless steel and the body of micropump machined from stainless steel. Tuckerman & Pease (1981) developed micropump used for microelectronics cooling based on liquid-phase chip cooling to consider flow rates of several hundred milliliters per minute. Lintel & Pol (1988) developed reciprocating displacement pump consisting of one and two pump chamber actuated by piezoelectric disc to be used in insulin delivery system. Esashi, Shoji & Nakano (1989) proposed normally closed microvalve and micropump fabricated on a silicon wafer. The normally closed microvalve actuated by piezostack actuator and verified the possibility to use a serial connection of two of those valves with a pressure chamber in between. In the year of 1990, Smits (1990) designed a peristaltic micropump with three active valves actuated by piezoelectric discs. Smits (1990) intended to use the micropump in controlled insulin delivery systems for maintaining diabetic blood sugar levels without frequent needle injections. Zengerle, Richter & Sandmaier (1992) presented a bulk micromachined membrane pump actuated by electrostatic actuator. The micropump consists of two passive check valves, a pump membrane and counterelectrode for electrostatic actuation with outer dimension of $7 \times 7 \times 2$ mm^3.

At present, the investigation and development of micropumps become crucial task in research area to produce the high performance micropumps according to its application and requirement. Micropumps can be classified in two major categories, which are displacement pump and dynamic pump. The description about the classification, concept and working principle of micropumps are explained further in Chapter 2.

1.2 Problem Statement

Micropumps as the actuation mechanism in microfluidics systems has been the issue in many researches area to determine its achievement in mobility of fluid, low power consumption and improved accuracy (Amirouche, Zhou & Johnson, 2009). In order to apply micropumps for medical uses, several factors must be taken into account such as biocompatibility of materials, effectiveness, and efficiency of the pump. Besides that, features of a micropump must also be considered such as actuation method, working principles, construction and performance of micropump parameters. Basic components of micropumps consist of pumping chamber, diaphragm, diffuser/nozzle element, inlet and outlet. These components play an important role to attain the high performance of micropumps. The micropumps diaphragm needs to deflect as large as it can to perform stroke volume and high compression ratio. Whereas the effectiveness and efficiency of the flow rectification is obtained based on the net flow rate and dependent on the diffuser/nozzle element design and geometry. In addition, materials of micropumps must have good chemical stability, biocompatibility, elasticity and economics scale (low cost).

Micropumps have complex design variables and require specific time to develop a pump system with high performance based on its application. In order to make the design of micropumps more systematic and efficient, the optimization tool of micropump variables is suggested. Many theories and methods are used to optimize the micropumps in order to acquire the high performance of micropumps. To design a micropump is a critical issue in choosing the optimum parameters to attain high net flow rate in forward direction (which fluid flow from inlet to outlet) with low power consumption and to avoid the fluid flow in reverse direction (which fluid flow from outlet to inlet). Hence, to develop a high performance and low power consumption of micropump, design optimization of micropump is suggested in this research by using the implementation of artificial intelligence (AI) approaches.

1.3 Research Objectives

The main objective of this research is to optimize the design variables of micropump by using AI approaches. In this research, the appropriate dimensions and parameters of the micropump are determined according to the application of the micropump. The other objectives are listed as follow:

i. To determine the optimum parameters for the micropump according to its application and requirement.

ii. To generate the optimization of micropump based on genetic algorithm (GA) and particle swarm optimization (PSO) methods.

iii. To develop a hybrid optimization method used to optimize the micropump design variables.

iv. To analyze and investigate the performance of micropump.

1.4 Research Scope

In this research, the performance of valveless micropump is studied. This research starts with the determination of the design variables for valveless micropump to be optimized using the implementation of AI methods. The variable parameters of valveless micropump are determined based on its application in medical application. The structure of valveless micropump is designed and simulated using ANSYS Workbench software whereas for the optimization algorithm is developed using MATLAB. This study focuses on GA, PSO and hybrid PSO-GA (denoted as HPSO-GA) optimization tools to optimize the design variables of valveless micropump. Simulation results obtained are compared for the three methods of optimization.

Three types of materials are investigated in this research to analyze the structural performance of the valveless micropump. These materials are silicon, silicon dioxide and stainless steel that have been successfully applied in medical application with the recent growth of drug delivery systems (DDS). Besides, these materials are extensively used as a good biocompatible material. However, a trend towards the use of polymers as substrate materials is growing as polymer materials are widely used in medical application. One of the most popular polymer materials in MEMS is polydimethysiloxane (PDMS). Although PDMS have some advantages and becomes a trend in MEMS fabrication, however this material has not selected to be included in this work. This is because the limitation of PDMS in term of the structure. PDMS is a soft structure and has the tendency to swell in most of the organic solvents besides its low Young's Modulus (several hundreds kPa) resulting in a bulging of the structures for applied pressure differences larger than 1 bar (0.1 MPa). Furthermore, the surface of

PDMS is hydrophobic which can encourage air bubbles to form in channels and PDMS has a high thermal expansion. In addition, PDMS is a material that ages, therefore after a few years the mechanical properties of this material can be changed.

In term of fabrication, it is almost impossible to perform metal deposition and dielectric deposition on PDMS. Thus, to perform various thin layer deposition of metal and dielectric deposition on PDMS required another material such as glass slide to be attached between PDMS and thin metal or dielectric layer. This is because PDMS can only easily attaches to a glass slide by using plasma treatment. Consequently have increased the fabrication cost by adding the glass slide.

1.5 Thesis Outline

This thesis is divided into five sections which consist of an Introduction in Chapter 1, Literature Review in Chapter 2, Research Methodology in Chapter 3, Results and Discussion in Chapter 4 and Conclusions and Future Work in Chapter 5. The description and content of each chapter is stated as follows:

Chapter 1 contains the brief introduction of the micropumps in microfluidics application. The problem statement, research objectives and research scope of this research are stated.

Chapter 2 presents a comprehensive review of micropumps classification, DDS and brief introduction on AI. Fundamental theory of the valveless micropump is also discussed in this chapter based on the concept and working principle. Optimization methods based AI approaches of micropumps from other studies are reviewed. Several