Design and operation of a bio-inspired micropump based on blood-sucking mechanism of mosquitoes

Tzong-Shyng Leu* and Ruei-Hung Kao†
Department of Aeronautics and Astronautics, National Cheng Kung University, No. 1, University Road, Tainan 701, Taiwan
*tsleu@mail.ncku.edu.tw
†jeffrey70140@hotmail.com

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The study is to develop a novel bionic micropump, mimicking blood-suck mechanism of mosquitos with a similar efficiency of 36%. The micropump is produced by using micro-electro-mechanical system (MEMS) technology, PDMS (polydimethylsiloxane) to fabricate the microchannel, and an actuator membrane made by Fe-PDMS. It employs an Nd-FeB permanent magnet and PZT to actuate the Fe-PDMS membrane for generating flow rate. A lumped model theory and the Taguchi method are used for numerical simulation of pulsating flow in the micropump. Also focused is to change the size of mosquito mouth for identifying the best waveform for the transient flow processes. Based on computational results of channel size and the Taguchi method, an optimization actuation waveform is identified. The maximum pumping flow rate is 23.5 µL/min and the efficiency is 86%. The power density of micropump is about 8 times of that produced by mosquito’s suction. In addition to using theoretical design of the channel size, also combine with Taguchi method and asymmetric actuation to find the optimization actuation waveform, the experimental result shows the maximum pumping flowrate is 23.5 µL/min and efficiency is 86%, moreover, the power density of micropump is 8 times higher than mosquito’s.

Keywords: Bio-mimetic; micropump; mosquito; Fe-PDMS.

1. Introduction

Micropump is the heart of a micrototal analysis system (µTAS) because it is used to drive the fluid flow. A highly-integrated and self-contained active micropump is essential to a successful µTAS. According to the review papers Nguyen, Huang and Chuan, most micropumps today can be categorized into two groups: mechanical pumps with moving parts and non-mechanical pumps without moving parts. The
mechanical pumps perform pressure work on the working fluid of the system via the moving boundary of reciprocating piston or oscillating diaphragm in the pumping chamber. Active check valves at the inlet and outlet of the pumping chamber are employed to control the direction of the pump flow. The non-mechanical pumps add energy continuously and directly to the working fluid by the interaction between the working fluid and the imposed fields, such as electromagnetic field, centrifugal force field, or ultrasonic wave field. There is a sub-category in mechanical micropumps called peristaltic micropumps that have three or more pumping chambers operating in a special peristaltic actuation sequence to drive the working fluid. Unlike the mechanical pumps with active check valves, peristaltic micropumps control the direction of the pump flow by varying the actuation sequence of the pumping chamber. Smits developed the first peristaltic micropump in 1990 using three pumping chambers driven by piezoelectric actuators operating in a 6-step peristaltic sequence to pump the working fluid and no check valve is employed, and the chamber diaphragms operate in an on–off mode. The main advantage of a peristaltic micropump is its simplicity in design and fabrication. The pumping chamber has no moving parts other than the pumping diaphragm. The main disadvantages of peristaltic micropumps are that each pumping chamber will have to be operated and controlled independently and that the pumping efficiency is relatively low because of the fact that no check valve is employed. The tiny pump system of female mosquitoes has the ability to suck more than three times the body mass of blood within a short period. Mochizuki and Kikuchi found mosquito pump volume with about $10^{-6}$ cm$^3$ has the same pumping power density as a pump with volume $10^3$ cm$^3$. Rapid intake of a sizeable amount of blood by blood-sucking mosquito is commonly induced by successive contractions and relaxations of their extrinsic visceral muscles, which function as dilators. Pumping muscles in the head of mosquitoes constitute a two-pumping organs, cibarial pump (CP) and pharyngeal pump (PP), are different from the traditional peristaltic micropumps that have three or more pumping chambers. Figure 1(a) shows X-ray microradiography of the CP and PP of a female mosquito and their corresponding volume variation. Figure 1(b) depicts CP and PP are found to be well coordinated with a phase

![Figure 1](image-url)
shift ($\alpha$) and time shift ($\beta$) that generate a net flow in one direction during the blood-sucking process. The phase shift $\alpha$ is the time difference between CP and PP chambers when they reach the maximum volume. The time shift $\beta$ is the time difference of the actuation starting time point of PP chamber relative to the maximum expansion time point of CP chamber. Another parameter $\gamma$ called volume ratio is defined as the volume change of PP divided by the volume change of CP.

2. Fabrication and Operation of Bio-Inspired Micropump

The fabrication process of bio-inspired micropump and experimental setup is shown in Fig. 2. Detailed fabrication processes are described in the following steps:

![Fig. 2. (Color online) (a) Fe-PDMS micropump fabrication process. (b) Photo of the fabricated micropump. (c) Sketch of the experimental setup. (d) Sketch of three testing positions of PZT magnet under the Fe-PDMS membrane.](image-url)
Step 1. Using SU-8-2075 to fabricate the channel-molding structures on a silicon wafer, the channel height is 80 µm, width is 600 µm, L1 is 25 mm, L2 is 13.75 mm, L3 is 2.5 mm, diameters of CP and PP are 4.5 mm (Fig. 2(a)), which are the optimization results from the lump model analysis with Taguchi method.

Step 2. The PDMS and Fe-PDMS are spin coated on SU-8 molding structures at 500 rpm for 30 s. Fe-PDMS is mixing 75 wt% ferro powder (diameter is 10 µm) and 25 wt% PDMS (Fig. 2(b)). PDMS thickness is about 500 µm.

Step 3. Peeling off PDMS and Fe-PDMS and bond it with a glass slide by using O₂ plasma. Two glass tubes with diameter 2 mm, and length 10 mm is packaged for input and output ports (Fig. 2(c)).

Step 4. Two PZT actuators (APA 120s) with Nd-FeB magnets are located at three testing positions under Fe-PDMS membranes (Fig. 2(d)). Then input driving signal to PZT actuators and measure the flow rate by imaging the moving water interface inside the glass tubes. In this study, there are five parameters (ε, θ, β, α and frequency) in the driving signal waveform, as shown in Fig. 3. Moreover, volume ratio parameter γ and efficiency η of the pump are defined as

\[ \gamma = \frac{\Delta V_{PP}}{\Delta V_{CP}}, \quad \eta = \frac{Q}{\Delta V_{CP}}, \]

where \( \Delta V_{CP} \) is maximum volume change of CP and \( \Delta V_{PP} \) is maximum volume change of PP during actuation. The waveform parameters are listed in Table 1.

![Fig. 3. (Color online) The parameters of driving signal for the micropump.](image)

<table>
<thead>
<tr>
<th>ε</th>
<th>Θ</th>
<th>β</th>
<th>α</th>
<th>Frequency (Hz)</th>
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Design and operation of micropump based on blood-sucking mechanism of mosquitos

Fig. 4. (Color online) (a) The optimization waveform. (b) The flow rate of different position of magnets. (c) Comparison of BDC with flow rate and efficiency.

3. Results and Discussions

By using Taguchi method\textsuperscript{5} $L_{16}(4)$ orthogonal array, the optimized driving signal waveform is found and shown in Fig. 4(a), when PZT magnet is actuated at a fixed bottom dead center (BDC) of $-20 \mu m$ and on the middle position of Fe-PDMS membranes. The best frequency is 4 Hz, similar to Ref. 4. According to the thickness of Fe-PDMS membrane and height of channel, total actuation depth can be as high as 580 $\mu m$. Three positions of PZT magnet under Fe-PDMS membranes (see Fig. 2(d)) are tested with fixed BDC of $-300 \mu m$. The flow rate results is shown in Fig. 4(b), where a maximum flow rate 23.6 $\mu L/min$ is found if the magnets locate on left side. The maximum flow rate is consistent if one exchanges the driving signals of CP and PP under the right position. Finally, the comparison of optimization waveform with magnets on left side with different BDC is shown in Fig. 4(c). As displayed in this figure, the best flow rate of BDC is $-300 \mu m$, but the maximum efficiency is 83% when BDC is $-400 \mu m$.

References