3D printed pump based on vibrating blades to actively manipulate fluid

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Abstract. This paper represents a novel working mechanism using vibrating blades to manipulate fluid based on 3D printing technology. A Finite Element Analysis (FEA) simulation has been established to research on working mechanism and driving ability of the vibrating blades-driven pump. The rising popular 3D printing technology is introduced to manufacture the pump, which decreases research time and cost drastically. Herein, a flat oscillating micromotor with extremely low working voltage and power is adopted to act as a random vibration source. The dyeing experiment shows the pump ability of directionally actuating fluid utilizing Fused Deposition Modelling (FDM) 3D printer. A testing system in weighing method is used to test flow rate of different pumps with various structures, receiving a maximum flux of 107.8 ml/min. The pump is characterized by applying structures into pump to actively control fluid. Furthermore, a micropump is printed by a high-resolution 3D printer, which shows potential applications of the 3D-printed vibrating blades-driven pump in manipulating microfluid.

1. Introduction
Manipulating fluid has been a hot topic of discussion and research for decades. Since Jan Smits produced the first pump for applications in controlling blood sugar level for avoiding injecting insulin frequently around 1980, so many researchers have been dedicated to creating novel pumps with more effective and excellent abilities [1]. While traditional pump devices could not figure out inherent problems, such as high working voltage or power, complex fabrication process and time-spending. What is more, most common pumps significantly depend on valve or special structure in inlet/outlet to actuate fluid [2].

In general, micropump could be classified into two kinds according to whether having moving sections, either mechanical micropump or non-mechanical micropump [3]. Typically, mechanical micropump tended to utilize diagram to vibrate periodically to pull-in fluid from inlet and extrude to outlet, achieving function of manipulating fluid. Polydimethylsiloxane (PDMS) was the most popular flexible diagram for high flexibility, biocompatible and electric insulation [4]. However, the technology was composed of photo-mask, lithography and PDMS molding, which took several days to get a device and decreased working efficiency greatly. What is more, when replicating PDMS-based 3D channel with multilayers, more manual work and time were required, resulting in unstable output ability for artificial influence [5].

3D printing technology, which was also called addictive manufacturing process, supported an alternative method for rapidly fabricating 3D devices with complicated structures in only one step. Moreover, the automated technology broke out traditional restriction in forming complex 3D structure and removed artificial influence in fabricating devices [6]. Recently, some researchers have developed
some fluid devices to effectively control fluid based the rising technique. Shallan et al investigated objective of cost-effective one-step fabrication of microfluidic microchips [7].

In this work, we applied three 3D printing technologies into manufacturing pumps based on a novel working principal to manipulate fluid. Firstly, the FEA model was presented which theoretically verified feasibility of motivating blades to actuate fluid directionally for application in pump. Then the dyeing experiment was executed to show capability of controlling fluid flow into desired destination of the vibrating blades. Furthermore, the integrated printing pump was made by a high resolution printer and utilized in flow rate test based on established testing system. These testing results indicated that the active-type mechanical pump could not only freely control flow direction, but also change flux by adopting different shapes of blade.

2. Simulation

A commercial FEA software COMSOL was introduced to compute the vibrating blade-driven pump model based on Fluid Structure Interface (FSI) theory [8]. The COMSOL software could customize functions or equations and couple multi physical fields, having ability to compute complex problems with higher reliability [9]. The working mechanism, driving fluid by confining blades in fluidic channel to vibrate periodically, was detailly researched. Herein, the fluid channel was designed with size of 1000 µm long, 200 µm wide and 100µ high. The simulation results were shown in Fig. 1.

![Simulation results of the blades-driven pump.](image)

**Figure 1**: Simulation flow rate results of the blades-driven pump. (a) Flow rate result about six blade structures when vibrating at 50 Hz/100 µm; (b) Vibrating amplitude/frequency versus flow rate of VB-3 structure.

Structure effects took significant role in actuating fluid for the principal. When adopting symmetric square blade in the fluidic channel, almost none fluid was pumped out of the outlet. While applying the V shape blade with one pair blade (VB-1), an obvious improvement could be seen in Fig.1a. If adding blades number to 3 pairs, flow rate increased 6.5 times to 26.68 nl/min comparing with VB-1. In addition, the connected beam played important role in improving driving capability. The driving performance raised nearly 2 times once adding a beam to link these blades. The beam could keep these blades moving in tone and supported another impetus for pushing fluid moving forward. Interestingly, only if changing blades distribution way like staggering two column V shape blades (VS), flux reached to 82.7nl/min, which indicated an effective method for improving working performance. Vibration amplitude and frequency were two most pivotal factors for all moving problems. So that two relationship curves about vibration frequency/amplitude and flow rate were simulated and computed as shown in Fig. 1b. When vibration frequency increased from 10 Hz to 200 Hz, flux kept rising with improving growth rate. Meanwhile, flow rate maintained nearly line increasement when changing vibration amplitude. The simulation amplitude result meant precisely outputting flow rate could be realized by controlling vibration amplitude rationally.
3. Experiment section
The prototype vibrating blades-driven pump device was designed to explore working mechanism and test flow rate by amplifying size of simulation models proportionately. 3D printing that was famous as low cost, non-toxicity, multi materials and rapid molding was applied in fabricating the pump (Shown in Fig. 2) [10]. So that we took advantages of three 3D technology crossing macro-scale to micro-scale to research the possibility or ability of the novel concept.

![Diagram of the pump using three 3D printing techniques.](image)

The first prototype pump with open chamber was made for the following dyeing experiment by combining the FDM printer (Dreamer, Flash forge, China) and rolling over process (Fig. 3a - 3c). The silica gel, with advantages of high flexibility, low cost and easily demold, was chosen as an ideal material for rolling over process. Fig. 3g showed the final silica gel pump.

![Schematic diagrams of 3D-printable prototype devices.](image)

Figure 3: Schematic diagrams of 3D-printable prototype devices. (a) – (c) Printing pump with a FDM printer; (d) – (f) Printing pump with the Polyjet 3D printer in one step; (g) – (i) Optical photos of printed pump with three 3D printing technologies.
Another integrated molding pump was manufactured by a high-resolution 3D printer Polyjet J750, which was characterized by high resolution and abundant materials (Fig. 3d - 3f). Especially, an excellent 3D printing material Polyvinyl Chloride called agilus was used to print the pump without valve in only one step. The chosen material had customizable Shaw stiffness, and a suitable flexibility (50º) was appointed. Then, a micromotor with extremely low working voltage and power acted as a reliable vibration source to motivate blades vibrate. Just attaching it under the bottom film with epoxy resin, the pump owned ability of directionally driving fluid. For further widen practical applications of the pump, a micropump based the principle was printed by a 3D printer (nanoArch S140 10 µm, BMF Precision, China) as shown in Fig. 3i. It showed the concept could be applied in micropump for manipulating microfluid directly.

4. Results and discussion
In this section, the above theory was validated experimentally by observing flowing phenomena and testing flow rate.

4.1. Dyeing experiment

Figure. 4: Optical photos of dyeing experiment in different time: (a) 0s; (b) 10s; (c) 30s; (d) 50s.

A dyeing experiment was executed to prove manipulation capability (Fig. 4). The silica gel pump was installed on the 3D-printed water container to keep two side walls fixed. And the water level was not higher than the container. Once applying low working voltage (3V) on the micromotor, the fluid would be impelled forward and led the colorant into the container. None colorant could be seen in fluidic channel after starting micromotor 50 seconds (Fig.4d). It could be concluded that the pump could drive fluid effectively from distribution of the colorant KMnO₄.

4.2. Testing flow rate
A testing system was established based on weighting method for testing flow rate shown in Fig. 5. Deionized (DI) water was regarded as working fluid with density of 1 g/ml. A direct current (DC) power (Gw INSTEK, GPD-3303s) was utilized to supply energy for the micromotor. And a peristaltic pump supplemented water for the reservoir continually to keep water lever higher than pump. After adjusting
level and starting the micromotor, the pump could drive fluid out to the breaker through tube. Flow rate could be computed according to number on the analytical balance.

![Optical photo of the testing system.](image)

Figure. 5: Optical photo of the testing system.

Herein, four pumps appearing in FEA simulation were printed and tested, and test results were shown in Fig. 6. The pump with square blades hardly had driving ability for extremely low flow rate, even leaving zero flux at applied voltage of 3V. When changing blade structure into V shape, the pump also outputted flux with 20.5 ml/min. If adding blades number to three pairs, flow rate reached to 37.2 ml/min. It meant structure scale was a critical factor on pump performance. Notably, a maximum flow rate could reach to 107.8 ml/min when staggering the blades. These testing results kept pace with simulation results, indicating reliability of the FEA.

![Testing results of the pump with six different blades.](image)

Figure. 6: Testing results of the pump with six different blades.

5. Conclusion

3D printing vibration blades-driven pump by three printers crossing macro scale to micro scale is researched. The pump is investigated analytically, computationally and experimentally to show ability of manipulating fluid. 3D printing has gained an increasing attention due to the recent advances in
forming complex 3D models and simplifying multi steps into one step. After validating the novel working principal based on FEA, the prototype pump is fabricated by the rising popular 3D printing process which decreases manufacturing cost and time dramatically. Combining FDM and rolling over process, the produced silica gel pump manipulates fluid powerfully according to the dyeing experiment, realizing function of directionally pumping. While the simulation locates in 2D and micro scale, the flow rate test results keep pace with simulation results to a certain extent. Whether simulation curves or experiment data, these results all show structure effects is a key parameter for improving driving performance. A micropump with V shape blades is printed, indicating potential applications of manipulating microfluid or nanofluid directly based the presented working principal.

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