論文の内容の要旨

論文題目　　1．題　目　　Development of a micropump for integrated microfluidic systems and pneumatic microactuator systems
（一体型マイクロ流体デバイスシステムと空気圧マイクロアクチュエータシステムの為のマイクロポンプの開発）

氏　　名　　李　愿世

Recently, microtechnology, the fabrication and application of structures with micrometer or submicrometer-scale features, is of great interest to scientists and engineers. Photolithography enabled microfabrication of not only electrical devices but also mechanical devices; such as micro-gears, micro-bearings, micro-motors, microvalves, micropumps, etc. Precision machining is also employed to fabricate micro-components where required, since lithographical fabrication has limitation in manufacturing nonplanar configuration.

Among those micro-components, micropumps are one of the key components to drive and control fluids that are of a typically sub-milliliter scale. Applications of micropumps include cell cultivation, fuel cell, cooling, micro total analysis systems, lab on a chip, and pneumatic microactuators. In order to apply a micropump for those applications, the following performance characteristics are required

- Wide range of flow rate covering from nL/min to several hundred μL/min
- High pressure discharge up to a gauge pressure of 100 kPa or higher
- Small in total system size so as to carry in a pocket
- Unlimited feed
- Flow stability
- Metering pumping that does not require flow sensors and feedback control.

A novel peristaltic pump has been designed based on the considerations raised above. The pump mainly consists of the two component groups: a disposable pumping channel unit and reusable parts (motor, connecting parts, housing and screwshaft). The pumping channel unit, made up of PDMS (polydimethylsiloxane) silicone elastomer (TSE3450, GE) through one-step molding, has eight circular pumping channels. The channels are evenly spaced along the inner surface, and each channel is linearly arranged and runs parallel with the others. The shaft rotating inside the pumping channel unit has a spirally arranged projection resembling a corkscrew on the surface which deforms and closes down the channels. While the shaft rotates, the pinched locations in the channels proceed to either way according to the direction of rotation, squeezing out the fluid inside. Fluid is introduced through the world-to-pump interface from the reservoir located outside the pump. Each channel has its own phase since the spirally arranged projection pinches different points of each channel. When the shaft stops moving, the flow rates at the moment stay zero, since the screw shaft works as a normally closed valve. Pulsations created by the peristaltic pumps may be drastically reduced by the combination of offset-phased channels. The pumping channels of our pump have all different phases, so this kind of pulsation reduction can be easily achieved by merging two anti-phase channels or more channels.

The performance of the pump was characterized by measuring the flow rate of water and the maximum discharge air pressure. The average flow rates were linearly proportional to rotation speeds and were not affected by back pressure, which proves that fact that metering pumping without feedback control or flow sensing. The maximum discharge air pressure measured was above 100 kPa. The flow rates measured ranged from approximately 3 to 280 μL/min for one pumping channel at frequencies of 3-180 rpm. However, pulsation remained. Pulsation was drastically reduced as the two anti-phased channels and more channels were merged since the flow rate phase of each channel is different.

Merge of two or more channels can significantly reduce the pulsation; meanwhile the number of useable channels also decreases. Also, there are still a certain amount of pulsation remained after merging the channels. Consequently, flow regulating without merging channel is desired for certain applications. To solve this problem, a new flow regulator was designed and tested.

The principle of the flow regulator is based on deformation of elastic pumping channel, which is conventional. But, the developed flow regulator works not passively but rather actively yet spontaneously without flow fluctuation sensing or additional control, by taking its design advantage. In addition, it reduces the dead volume in the system, whereas other conventional approaches, so called pulsation dampeners that use deformation of soft membrane, increase dead volumes and required pressure. The flow regulator was designed as a part of screw shaft. The flow regulator doesn’t close the channel but compensates the flow fluctuation caused by valve opening, or sudden release of pinching the channel, since its width is wider (2.5 mm) enough than the spiral projection (1.5 mm) of the screw shaft, thus its movement is smaller and the compensated flow volume can be assumed proportional to the gap difference between the pumping channel and the flow regulator.

It was shown through the tests that pulsations were significantly reduced as the flow-regulator-integrated screw shaft was used. The proposed flow regulator is beneficial because it doesn't require much space or energy source, which contributes to small total system size, small dead volume, and low cost. Compared to the result of two-channel merging method, residual pulsation level was high, since the prototype flow regulator was not machine-polished, which causes unexpected pulsations. Yet, phase offset method is still able to be used together.

To integrate microchannels with the pump, a new fabrication method for manufacturing nonplanar microchannels is proposed.

Generally, it has been regarded that micropumps are not likely to be suitable for pneumatic actuators which requires a big volume of air and high air pressure, since the flow rate ranges of micropumps are usually very low (several nanoliters per minute to several milliliters per minute). Fortunately, pneumatic microactuators do not require as much, since they are very tiny. Also, working pressure range is relatively smaller than macro-scale actuators. Consequently, micropumps can be used to drive pneumatic microactuators, once the dead volume is reduced enough. Feasibility for pneumatic microactuator application was investigated through a series of organized tests.

Through the experiments, it was shown that the newly developed pump generate not only positive pressure but also negative pressure. Further, performance of normally-closed valve was shown. However, it took about 10 s to reach 100 kPa with using 8 channels at 150 rpm, which is the biggest problem the pump has.

Two types of pneumatic microactuators are studied to learn feasibility for the pump. A pneumatic balloon actuator (PBA) and a half-bellows type actuator are tested. A PBA, which works within the pressure ranging from 0 to 100 kPa, was designed utilizing finite element method (FEM) and fabricated. The performance was as estimated using FEM simulation. A bellows-type microactuator, which works within the pressure ranging from -50 to 100 kPa, was also fabricated and tested. It was demonstrated that the developed pump can be used for pneumatic microactuator applications.

The slow motion of the microactuator is a critical problem when it comes to a practical application. It is due to the low flow rate of the pump. Higher flow rate may be achieved by rotating the motor fast or by enlarging the inner diameter of the pumping channels. However, fast rotation causes more heat which affects the durability. Also, making a bigger pump is not favorable. Compressibility of air is one of the reasons why much flow rate is required for pneumatic actuation. Hence, use of incompressible fluid, or liquid, may be a solution. However, hydraulic actuation has some drawbacks such as contamination and safety issues since microactuators are breakable compared to macro-size pneumatic actuators. Furthermore, it is not suitable for the developed pump due to the pulsation which can keep it from precise control.

To overcome the disadvantages of pneumatic actuators and to exploit the advantages of hydraulic actuators, a hybrid method combining the advantages of pneumatic and hydraulic actuation is proposed. The hybrid actuation method is only applicable to microactuators where gravity can be neglected and surface tension force is dominant. Otherwise, air inside the actuator would be discharged when the actuator was tilted. It was shown through the tests that the hybrid method drastically contributes to expedite the movement speed of pneumatic microactuators with better safety, in case of break, is retained.

Integrating a pump unit with a microchannel unit or pneumatic microactuators is an important issue when it comes to practical applications. The pump and motor are connected serially with a cylindrical shape. Consequently, microchannel or microactuator units need to be connected along the shape. A novel method for the fabrication of nonplanar devices is proposed. Since the pumping channel unit, microchannels, and pneumatic actuators can be made out of PDMS. Thus, either microchannels or pneumatic actuators can be combined with the pumping channel unit without connecting parts. Two fabrication methods are discussed and demonstrated.

A novel linear-peristaltic micropump has been developed. The results of experiments and simulations support the above mentioned requirements. Hence, the new pump may have a wide range of applications including microfluidic analysis systems and pneumatic microactuators.