A micro-vibrator based cross-junction microfluidic system for formation and control of droplets

Yongtao Tang¹, Yong Chen², Kang Wang² and Yiran Miao¹

¹ Nuclear Power Institute of China, Chengdu, China
² School of Electrical Engineering Southwest Jiaotong University, Chengdu, China
chenyong.sclz@gmail.com

Abstract. Microfluidic droplet technique is a novel technology developed on the basis of microfluidics to study the formation, manipulation and application of microdroplets of a few micrometers size. It drastically enhances the advantages in terms of low consumption, automation and high throughput and is widely used in chemical, microelectronics, materials science, biology and biomedical engineering etc. Nevertheless, there are still a series of problems about the formation and control of droplet. To generate the given droplets and control their size, a micro-vibrator based cross-junction microfluidic system is designed and implemented, where the size of droplet can be dynamically adjusted via the flow rates of two phase fluids and the vibrant frequency of micro-vibrator. Moreover, a closed-loop control framework with certain special mothold, i.e., iterative learning control (ILC), is discussed to assist the formation of droplets. The experimental results confirm the feasibility of proposed scheme.

1. Introduction
Microdroplet technology refers to the technology developed on microfluidic chips to study the generation, manipulation and application of microdroplets ranging in size from several micrometers to several hundred micrometers [1]. Due to the advantages of small size, no diffusion and cross-contamination between samples, stable reaction conditions, microdroplets have been the ideal microreactor for the chemistry and life science research, such as chemical synthesis [2], microextraction [3], enzyme synthesis [4] and cell encapsulation [5] etc. In these applications, it is very essential to generate the given droplets and control their size.

At present, many methods have been developed to deal with the formation of droplets. The main principle is that the physical force of the flowing fluids causes the deformation of fluidic surface under the restriction of geometry structure of microchannel, so as to generate the discrete droplets. The T-junction method [6], flow focusing method [7], co-flowing method [8] fall into this category. Furthermore, to increase the instability of the interface, some external driving force is applied to the flow field to break the discrete phase, such as the optical control method [9] and the micro-vibration method [10] etc.

Nevertheless, since the complex dynamics of the fluids, the size of droplets is difficult to be precisely controlled. To solve this problem, a series of research results have been proposed. Some researchers try to find the mathematical model of droplet formation, thus realizing the prediction for size of droplet. There are mainly two methods, that is, data fitting and geometric description. Data fitting means that the relationship between the flow rate ratio and the size of droplet is obtained by analyzing a large number of experimental results. For example, \( y = a + b\phi \), where \( y \) is the
dimensionless volume of the droplet, $\phi$ is the flow rate ratio of the discrete phase to the continuous phase, and $a$ and $b$ are constants. Researches on this can be found in [11], [12]. The method of geometric description is to observe and analyze the process of droplet formation, and finally gets the geometric relation between the size of droplet and the flow rate ratio. The most representative research can be found in [13], [14].

Other attempts are to introduce the modern control methods into microfluidics to handle the lumped uncertainties of fluids. In [15], the researchers used the system identification method to obtain the model of the droplet formation, then adopted the closed-loop feedback control method combined PID controller to adjust the size of droplet. These studies partly solve the problem of controlling the size of droplet, however, they all have a common problem, namely the dependence on the model. As we all known, there is no effective method to obtain accurate model of droplet formation. On the other hand, model-based feedback control methods would result in poor control performance because of the existence of model uncertainties.

As a data-driven control method, when the control task is periodic and repeatable, iterative learning control (ILC) can correct the current input signal by the previous trial information, eventually improving the control quality [16]. ILC can learn from the previous control trials, so less prior information on system model is required. Since ILC is not dependent on the accurate model of dynamic system, the high uncertainty of complex system can be handled in a very simple way. The ILC method has been used in the microfluidic system, the precise control of the position of two-phase laminar flow interface in Y-Shaped microfluidic channel is achieved via the ILC mechanism in [17].

In this paper, we will focus on the issues about the formation and control of droplets in the cross-junction microfluidic system, where the controllable components of system include the micro-vibrator and syringe pumps, and the controlled object is the size of droplets. The main contributions of this paper include: (1) The system for dynamically adjusting the size of droplet via the flow rates of two phase fluids and the frequency of micro-vibrator is designed and implemented; (2) A closed-loop control system, including the simple control framework, i.e., ILC method, is discussed to assist the formation of droplets; (3) Some experimental results are given to verify the effectiveness of system.

2. Design of Microfluidic System
In this section, we introduced the microfluidic network, which includes the cross-junction microfluidic chip, micro-vibrator. The principle for formation of droplets is reviewed informally. Finally, a simple control system is given for the formation and control of droplets.

2.1. Microfluidic Network
Fig. 1 illustrates the basic structure of microfluidic network, where a micro-vibrator based on the piezoceramic is loaded onto the microfluidic chip, which is constructed in polydimethylsiloxane (PDMS) material using standard soft lithography techniques [18]. A microfluidic chip including two microfluidic networks is shown in Fig. 1(b).

The geometric structure of cross-junction microfluidic is shown in Fig. 1(a), which includes a central channel and two side channels. Two incompatible and incompressible Newtonian fluids are selected as the continuous phase and the discrete phase. During the droplet formation, the discrete phase is injected into the microfluidic network from the central channel at a given volumetric flow rate, and the continuous phase is injected from the side channel at another volumetric flow rate. When the two phase fluids meet at the cross-junction, the continuous phase squeezes the discrete phase, thus resulting in the latter to deform. Under the sustaining squeeze of continuous phase, the discrete phase breaks, eventually forming droplet. Clearly, the faster the flow rate of discrete phase, the larger the size of droplet. The faster the flow rate of continuous phase, the smaller the size of droplet. Let $s \in \mathbb{R}$ denote the size of droplets, $v_d \in \mathbb{R}$ and $v_c \in \mathbb{R}$ denote the flow rates of discrete phase and continuous phase, respectively, the formal form can be written as follows
Figure 1. The microfluidic network.

It is very inefficient to control the size of droplet only through the action of continuous phase, since the discrete phase only breaks up into droplets far from the cross-junction. Hence, some external forces are applied to the discrete phases to aid the formation of droplets, by virtue of a micro-vibrator based on the piezoceramic actuator. The micro-vibrator shown in Fig. 1(d) is embedded in the microfluidic chip and placed at the upstream of central channel. Since the vibration increases the instability of surface of discrete phase and thus accelerates the formation of droplets, one could get the following relationship

\[ s \propto \frac{v_d}{v_c} \]  

(1)

where \( p \in R \) denotes the frequency of vibration. That is, the size of the droplet is inversely proportional to the frequency of vibration.

Remark 1: It should be pointed out that the principle of formation of droplets adopted in this paper obeys the jetting regime since we have empirically found that the controllability is better than other methods. More information about the formation mechanism of droplets can be found in [19].

2.2. Control System

To control the size of droplets, one considers a control system whose components consist of a microfluidic chip, two syringe pumps, a micro-vibration subsystem, a microscope and a computer. The continuous phase and the discrete phase are respectively injected into the two entrances of microchannel at the given flow rates using two same syringe pumps (Baoding Longer Precision Pump, China). The micro-vibration subsystem, including the vibrator and control unit, is provided as auxiliary system. The microscope (XSP-24, Phenix, China) is used to observe the formation of droplets and upload the results to the computer. The computer uses the image processing software to analyze and obtain the related information. Since the syringe pumps and micro-vibrator all can be accurately tracked and controlled as previously mentioned, a simple closed-loop control system for formation and control of droplets could be established as shown in Fig. 2.
Figure 2. The control framework.

When two phase fluids meet and occur deformation, some droplets with different size could be obtained if the flow rates are appropriate luckily. Most of the time, however, the phenomena that two streams flow in parallel without droplets can be observed. To assist or accelerate the formation of droplets, it is essential to turn on the micro-vibrator which is controllable. According to the feedback from the microscope, one can adjust the flow rates of two phase fluids and the frequency of vibration to obtain the desired droplets. By (1) and (2), the adjusting process is rather easy since the size of droplet $s$ shows a clear monotonicity with respect to $v_d$, $v_c$ and $P$, respectively.

Remark 2: We just introduced informally the mechanism of control system, what kind of specific control method could be determined based on the physical environment and the experience of the researchers.

3. Idea of Iterative Learning Control

In this section, our goal is to introduce the idea of the ILC to enhance the controllability of microfluidic system with respect to the formation of droplets.

Since the output is measured based on image processing, there are some implementation issues in the instantaneous feedback. To overcome this, a control framework based on ILC is proposed, where ILC is open-loop in time domain and closed-loop in iteration domain. The ILC controller can improve the current control input based on the previous trials and thus requires little information about the model. The structure of ILC scheme is shown in Fig. 3, some memory components are used to record the control signals of previous trials, i.e., $u_{k-1}$ and $s_{k-1}$, and the feedforward loop in iteration domain is used to improve the current control signal $u_k$ via previous $u_{k-1}$ and $s_{k-1}$.

Consider the flow rates of the two phase fluids and the frequency of vibration as inputs, using $u \in \mathbb{R}^3$ to denote, that is $u = [v_d, v_c, P]^T$. And use $s$ as the output of the system. The mapping relation of output and input can be assumed as the following form

$$s_k = f(u_k)$$

(3)

where the subscript $k \in \mathbb{N}$ denotes the $k$ -th control trial, $f(\cdot)$ is a partially unknown function.

The object of control system is to generate the droplet with desired size, which is denoted as $s_d$, so the contraction-mapping (CM)-based ILC rule is designed

$$u_k = u_{k-1} + (s_d - s_{k-1})q$$

(4)
where \( q \in R^3 \) is the learning gain. Based on (1) and (2), \( f(u) \) is a monotonic function with respect to \( v_d, v_c \) and \( p \), respectively, so it is easy to choose an appropriate value for \( q \), i.e.,

\[
q = \frac{u_2 - u_1}{s_2 - s_1}
\]

Remark 3: As we all known, in the cross-junction microfluidic system, the formation of droplets is not only related to the flow rates ratio of the discrete phase to the continuous phase, but also to the the distance between micro-vibrator and the cross-junction. At present, there is no effective modeling method to accurately describe the relationship of the size of droplets with the flow rates ratio and distance. It is especially emphasized here that (1) and (2) are only empirical. As one of model-free methods, ILC has low requirement on the prior information of control system. Meanwhile, the realtime feedback of output is not essential since ILC supports the offline control. Hence, ILC is an ideal technique for microfluidic system, and is specifically introduced here.

Remark 4: It is worth emphasizing that using the modern control methods to design the controller is flexible, such as discrete-time PID control, iterative learning control, etc. In this paper, the mechanism of control framework is just introduced informally, please refer to [20], [21] for more details.

4. Experimental Results
In this section, we verify the feasibility of the proposed scheme for the formation and control of droplets via experiments. The main contents include that using the designed framework to implement the cross-junction microfluidic system based on micro-vibrator, and the droplets with given size are formulated based on the idea of ILC.

4.1. Implementation of System
To illustrate the microfluidic system we designed, a platform for generating droplets is established, as shown in Fig. 4, where the structure of system follows the framework in Fig. 2. The control inputs are composed of two parts, in which two syringe pumps are utilized to regulate the flow rates of two phase fluids, and the control unit of micro-vibrator is used to vary the vibrant frequency of the piezoceramic actuator. The goal of system is to stably produce droplets with uniform size in the main channel of microfluidic chip, where the microscope acting as the sensor is employing to observe the process of droplet formation. Particularly, in the micro-vibration subsystem an OLCD screen is installed to display the the magnitude of vibrant frequency, which is conducive to enhance the control accuracy of system.

Figure 4. The microfluidic system for formation and control of droplets.
During the experiments, the oil was chosen as the continuous phase, water as the discrete phase, both of which were injected into the microchannel from respective inlet. The microfluidic chip, fabricated using standard soft lithography method, is placed horizontally on the microscope carrier, and connected with the syringe pumps and the control unit of micro-vibrator via the polyethylene pipe or wires respectively, where the widths of the central channel and the side channel of chip are 100µm, 50µm, respectively, and the depth of channel is 50µm. More information of experimental parameters are given in TABLE 1.

| Description                                           | Symbol | Value |
|-------------------------------------------------------|--------|-------|
| The widths of central channel (µm).                   | \( w_c \) | 100   |
| The widths of side channel (µm).                      | \( w_s \) | 50    |
| The depth of all channel (µm).                        | \( h \)  | 50    |
| The viscosity of discrete phase (mPa • s).            | \( \eta_d \) | 4.9   |
| The density of continuous phase (kg • m\(^{-3}\)).    | \( \eta_c \) | 110   |
| The viscosity of discrete phase (mPa • s).            | \( \rho_d \) | 139.7 |
| The density of continuous phase (kg • m\(^{-3}\)).    | \( \rho_c \) | 1174  |

4.2. Formation of Droplet
Under the guidance of the proposed control framework, some droplets shown in Fig. 5 were generated by the microfluidic system with micro-vibrator. Particularly, Fig. 5(a) demonstrated the formation of droplets when the micro-vibrator is turned off. It could be found that the trial is inefficient, and the generated droplets are uneven in size. In addition, it is worth noting that the two droplets with different size might merge into one droplet at the place far away from the cross-junction, which is bad for other experiments based on micro-droplets. Fig. 5(b) shows the formation of droplets after turning on the micro-vibrator. Despite there is still certain deviation, the results have been improved clearly. Finally, in Fig. 5(c), the droplets meeting given requirements are generated via the corresponding adjusting. Experimental results confirmed the effectiveness of proposed scheme.
limitation of space and time. More rigorous derivation, including the formation mechanism of droplet and the experimental procedure of control scheme, will be explained in future work.

5. Conclusion
In this paper, for the formation and control of droplets, a cross-junction microfluidic system is established, where a controllable micro-vibrator based on piezoceramic is implemented to serve as the subsystem of microfluidic network. Simultaneously, a closed-loop control framework was proposed to generate the droplets with given size. As a special method, the idea of ILC is introduced to assist the formation of droplet. Finally, the effectiveness of scheme is verified via experiments.

6. References
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**Acknowledgments**

The work was partially supported by the National Natural Science Foundation of China under Grants 61773323, 61433011, 61603316, 61733015, the Fundamental Research Funds for the Central Universities 2682018CX15, and the Sichuan Science and Technology Program under Grant 2019YFG0345, 2019YJ0210.