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Vortex generation and control in a microfluidic chamber with actuations

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In this paper, we present a novel method for vortex generation and control in a resonator-shaped microfluidic chamber with actuations. By varying the actuation conditions, including the working transducers, frequency, and voltage, two regimes of vortices, clockwise vortex (CW vortex) and counter-clockwise vortex (CCW vortex), are generated in the chamber. We show that the direction of the vortex can be conveniently shifted from clockwise to counterclockwise by switching the working transducers without interrupting the flow, and the intensity of the vortex can be regulated by the actuation frequency and voltage. It is proposed that the vortex generation in the present case is due to the instability of the actuation-induced pulsatile flow through the sudden expansion part at the outlet of the chamber, while the vortex control is realized through the asymmetric flows in the chamber induced by the upper or lower transducers. The reported method of vortex generation and control can be applied in microfluidic operations for mixing enhancement of multiple reagents and distribution of microparticles and nanoparticles. *Published by AIP Publishing.* [<http://dx.doi.org/10.1063/1.4971314>]

I. INTRODUCTION

Microfluidics, which is involved in the science and technology of manipulating small amounts of fluids in networks of micro-channels, has broad applications in chemistry, medicine, and biology, owing to its numerous advantages of simple manipulation, low cost, less sample consumption, and so on.¹ Vortical flows are widely applied for flow control in many microfluidic devices, such as cell centrifuges, mixers, sorters, concentration gradient generators, and reactors.^{2–7} However, due to small channel dimensions and low flow rates, the flows in microfluidics tend to be laminar and dominated by viscosity of the fluids. Thus, it is always challenging to generate controllable vortices in microfluidic systems for applications. To produce vortices, several well-designed configurations have been used in the microfluidic systems, including herringbone structures, zigzag channels, serpentine channels, and flow focusing systems.^{8–12} These methods of vortex generation rely on the advection flow caused by complex configurations and geometries of the microchannels, and they are so-called passive methods. Mengeaud *et al.*⁸ investigated the vortical flow in a zigzag microchannel for the flow rate of 22 500 ml/h (Reynolds number $Re = 267$) and further numerically demonstrated that the recirculations could be generated at the turns when the inlet flow rate was above a critical value (6910 ml/h, corresponding to $Re = 80$). Liu *et al.*⁹ studied the flow in a three-dimensional serpentine channel and confirmed the occurrence of the vortical flow at the flow rate of 72 ml/h (corresponding to $Re = 70$). Subsequently, Kang *et al.*¹⁰ numerically studied the flow transition in this kind of channels from regular to vortical flows and found that the critical Reynolds number was about 50, corresponding to the inlet flow rate of 51.4 ml/h. Strook *et al.*¹¹ utilized herringbone structures on the floor of the channel to generate advection or even chaotic flows and they obtained a good mixing performance caused by the generated vortices in the channel at the working flow

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rate of 612 ml/h. In these passive methods, the applicable working flow rate was generally high in order to generate the desired vortical flows, and the high flow rate caused a waste of the precious bio-samples or reagents. An alternative approach, active method, can effectively generate vortical flows with lower flow rate. It involves introducing external actuations, such as electrokinetic force, magnetic force, acoustic actuation, thermal effect, and even external air flux.^{7,13–19} Electrokinetic force, in particular the phenomenon of “induced-charge electro-osmosis” (ICEO), can serve as an effective tool for vortex generation in microfluidics. Thamida and Chang¹³ found that when a sufficiently strong electric field acts on the ionic charge induced around a polarizable surface, the interaction between the induced ions and the external field created downstream a macro-scale vortical flow. Liu *et al.*¹⁴ studied the manipulation of particles by means of the microvortices generated by ICEO near a polarizable wall. However, this method could only be applied to the electrolyte solution in the neighborhood of polarizable surfaces.^{13–15} Park and Wereley⁷ presented a method of rapid generation of microvortices induced by alternating current electric fields together with a laser beam. In addition to the indispensable laser irradiation and electric fields, this method also required transparent fluids and precise manipulation to position the focal plane to produce vortices. Zhu and Nguyen¹⁶ demonstrated a method of vortex generation by means of the interaction between a magnetic field and a ferrofluid in a microfluidic chamber. This magnetic method was only applicable to ferrofluids or the fluids with magnetic particles. Kim *et al.*¹⁷ demonstrated the generation of multi-vortices by using natural convection in conjunction with alternating heating for micromixing and polymerase chain reaction (PCR) tests. In their study, the sensors and heaters were embedded in the walls of the channel in advance. This method could damage or influence the properties of the samples or reagents which were sensitive to temperature variation. Acoustic actuation has been widely applied in vortex generation and control in microfluidics due to its great superiority compared to the aforementioned methods: high efficiency, non-damage, and no limits on the properties of fluids, such as conductivity, magnetism, and transparency. By introducing air bubbles in a microfluidic channel, the vibration of the air–liquid interface can induce steady streaming flows around the bubble and this effect is known as cavitation microstreaming. Wang *et al.*¹⁸ investigated the vortical flows induced by an oscillating bubble driven by ultrasounds at different frequencies in a microfluidic channel with a cavity. Ahmed *et al.*⁶ designed a single-bubble-based vortex generator by trapping an air bubble within a “horse-shoe” structure. By applying acoustic waves, the trapped air bubble was excited at its resonance frequency, leading to a pair of counter-rotating vortices that extended from the front side to back side of the horse-shoe structure. In this method, the foreign gas bubbles need to be introduced and trapped in the channel in advance and there is usually a problem associated with temperature rise at high frequencies.³ Therefore, in the current methods of vortex generation and control, there exist some drawbacks causing inconvenience in practical applications, and the novel and simple methods of vortex generation and control in microfluidic systems remain to be an attractive research topic.

In this work, we demonstrate a novel method to generate controllable vortices in a microfluidic chamber incorporated with PZT (Lead Zirconate Titanate) actuations. Especially, the direction of the generated vortex can be shifted from clockwise to counterclockwise by simply switching the working transducers without interrupting the flow. The flow patterns are visualized by tracing fluorescent dyes and particles in the fluid and recorded by a CCD camera. We carry out thorough experiments to study the effects of the applied actuation conditions, including the working transducer, frequency, and voltage, on the direction and intensity of the generated vortex. Specifically, the flow velocity in the outlet channel at various actuation frequencies is measured in order to explore the mechanism of the vortex generation.

II. EXPERIMENTAL METHODS

The configuration of the microfluidic chamber used in the experiment is shown in Fig. 1. The chamber is made by two PMMA (polymethylmethacrylate) plates sandwiched by a dry adhesive layer of 300 μm thickness (Arclad 8102 transfer adhesive, Adhesives Research, Inc.). The chamber contains two parts, a 16 mm diameter circular chamber and a nozzle with an acoustic resonator

FIG. 1. Illustration of the microfluidic chamber and experimental setups. (a) Side view of the configuration of the microfluidic chamber. (b) Top view and geometric dimensions of the microfluidic chamber. (c) Schematic illustration of the microfluidic chamber. (d) Schematic illustration of the experimental setups. The velocity in the rectangular region—zone 1 is measured.

profile. The geometric profile of the chamber can be described by

$$y = \begin{cases} \sqrt{8^2 - x^2}, & -8 \leq x \leq 4, \\ 0.5e^{0.1011(30-x)}, & 4 \leq x \leq 30. \end{cases} \quad (1)$$

It has been demonstrated that this profile of the nozzle can be used as an acoustic resonator to achieve high amplitude pressure fluctuations.^{20,21} Three inlets at an angle of 36° are connected to the chamber by a straight channel of 10 mm in length and 1 mm in width, and another straight channel is connected to the other end of the chamber to form the outlet. A PZT disk is attached to the bottom of the circular chamber. The PZT disk consists of a piezoelectric ceramic layer of 15 mm diameter and a brass sheet of 22 mm diameter. The ceramic layer is divided into two transducers which can be actuated separately—Transducer A and Transducer B, as shown in Fig. 1(c). The microfluidic chamber was fabricated by a laser cutting machine (Universal M-300 Laser Platform, Universal Laser Systems, Inc., Arizona, USA).

The schematic of the experimental setup is illustrated in Fig. 1(d). The degassed DI water without fluorescent dye is supplied to the microfluidic chamber at Inlets 1 and 3, and the dyed DI water is supplied to Inlet 2. The flow rate of each inlet is separately controlled by a syringe pump (KD Scientific, Inc., USA). A high speed CCD camera (Phantom V711, Vision Research, USA) is mounted on top of the chamber to record the flow patterns. The PZT disk is driven by an external signal generator (33120A, Hewlett Packard) and an amplifier (790, PCB Piezotronics) and the working transducer can be altered conveniently by a switch.

To quantitatively characterize the vortex intensity, a MATLAB code is used to process the recorded images. A cross line C–O–C' (Fig. 1(d)) through the center of the chamber is selected to analyze the fluorescent intensity. An indicator of vortex intensity is calculated using the following expression:

$$\text{Vortex Indicator (\%)} = 1 - \sqrt{\frac{1}{N-1} \sum_{i=1}^N \left(\frac{\bar{I}_i - \bar{I}_{ave}}{\bar{I}_{ave}} \right)^2}, \quad (2)$$

where N represents the total number of points examined along the cross-line C–O–C', $\bar{I}_i$ is the normalized fluorescence intensity at each point, and $\bar{I}_{ave}$ is the mean of normalized fluorescence intensity at all points. Clearly the indicator is the index of the vortex intensity and increases with enhancement of the vortex. When the fluids are perfectly mixed, the value of the vortex indicator is equal to 100%.

To measure the velocity in the rectangular region—zone 1, the flow patterns of the fluids which are seeded by micron-sized particles are recorded by the CCD camera at first and then the recorded images are transferred to a Particle Image Velocimetry (PIV) software platform (DynamicStudio, Dantec Dynamics, Denmark) to calculate the velocity fields. In order to obtain high quality signal with around 2-5 particles per interrogation spot, the traceable polystyrene microspheres (Fluoro-Max, Diameter 4.8 μm , Thermo Scientific) were diluted with degassed DI water to act as the working fluid. The velocity field of the flow was obtained by calculating the particle displacement of two consecutive images by means of DynamicStudio.

A piezoelectric actuator converts an electrical signal in terms of voltages into a mechanical displacement (called stroke). As shown in Fig. 2(a), the two separate transducers are affixed to a circular brass sheet to form the PZT disk and the PZT disk will be vibrating as a whole when either transducer is actuated. When the semi-circular transducer—Transducer A or B—is actuated, the vibration of the PZT disk is considered as the small deflection of a thin circular plate with off-center loads. As illustrated in Figs. 2(b) and 2(c), the “vibration center”—the point in the PZT disk with maximum amplitude—is not located at its geometric center of the chamber, so that the flow induced by the actuations will be asymmetric in the chamber. In experiments, the flows were recorded by a camera from the top of the PMMA plate opposite to the PZT disk and thus, Transducer A and B in Fig. 2(a) are shown upside down compared to the illustration in Fig. 1(c).

III. RESULTS AND DISCUSSION

A. Visualization of vortex generation and control by fluorescent dye

Using the fluorescent dye as flow tracers, the flow patterns inside the microfluidic chamber were recorded by the camera after the actuation was switched on. The flow rates for the three inlets, 1, 2 and 3, were respectively set as 4.5 ml/h, 1 ml/h, and 4.5 ml/h such that the total flow rate through the chamber was 10 ml/h. The PZT was actuated at 100 V and 1.5 kHz. Transducer A was triggered at first and meanwhile the flow patterns were recorded; when the flow was fully developed, the actuation was turned off; after the flow was resumed to its original state, Transducer B was triggered. The vortex development with time for Transducer A and B is presented in Figs. 3(a)–3(e) and 3(g)–3(k) (Multimedia view), respectively. It is seen that, without actuations (Figs. 3(a) and 3(g)), the fluids flow separately through the chamber and the interface between the fluids is very clear, which means that the flow is laminar. Within a few seconds of turning on the actuation, the fluorescent-dyed fluids which come from Inlet 2 are distorted and swirled to the whole chamber

FIG. 2. (a) Illustration of the PZT disk. The PZT disk consists of two separate transducers and a brass sheet. (b) The vibration profile of the PZT disk when Transducer A is working. (c) The vibration profile of the PZT disk when Transducer B is working.

as shown in Figs. 3(b)–3(d) and 3(h)–3(j). In both cases, a large vortex is formed, occupying the whole chamber. However, the regime of the vortex is different for the two cases in terms of the vortex direction: when Transducer A is actuated, the vortex rotates in the clockwise direction, which is denoted as CW vortex; when Transducer B is actuated, the formed vortex is in the counter-clockwise direction, which is denoted as CCW vortex. In Figs. 3(e) and 3(k), the fluorescent

FIG. 3. Recorded images of the vortex development with time and the dashed lines in (a) and (g) indicate the working transducer. Clockwise vortex (CW vortex) is generated when Transducer A is actuated (a)–(e) and counter-clockwise vortex (CCW vortex) is generated when Transducer B is actuated (g)–(k). The actuation voltage and frequency are 100 V and 1.5 kHz, respectively, and the flow rate is 10 ml/h in total. The traces of particles of CW vortex (f) and CCW vortex (l) are in accordance with the flow patterns of fluorescent dyes, respectively. (Multimedia view) [URL: <http://dx.doi.org/10.1063/1.4971314.1>]

fluid is continuously swirled and finally, the interface between the fluids disappears and the flow is fully developed. In addition, we also used the suspension of microparticles in the flow as the tracer to display the flow characteristics of the generated vortices by stacking a large amount of images of the fluid flow at various moments. As shown in Figs. 3(f) and 3(l), the traces of particles clearly present the generated vortices in the chamber, in accordance with the flow patterns of fluorescent dyes. It is noticeable that the generated vortex is three dimensional in nature because the flow is induced by the up-and-down vibration of the PZT disk in the height direction. In the experiment, the vortex direction is shifted conveniently by selecting the working transducer without altering the device or interrupting the flow ([supplementary material S1](#)). This method of vortex generation has advantages over other methods in many aspects. It has no requirement on the flow rates and properties of working fluids such as conductivity or magnetism. It can generate large-scale vortices without the need to introduce and trap external gas in advance. It is non-intrusive and damage-free without noticeable temperature rise. Besides, the controllable vortex direction via a switch is a novel and useful feature, which may promote the maneuverability of microfluidic operations for mixing enhancement of multiple reagents and distribution of microparticles and nanoparticles.

B. Effects of actuation frequency and voltage on the generated vortex

The dependence of the vortex on actuation frequency is presented in Fig. 4. The frequency is varied from 1 kHz to 4.5 kHz, and the applied voltage and flow rate are 100 V and 10 ml/h, respectively. The flow patterns in Fig. 4 were recorded when the flows were fully developed at 40 s, and the vortex intensity at this time was calculated by using Eq. (2). From Fig. 4, it is clear that when either Transducer A (solid line) or Transducer B (dashed line) is actuated, there exists an effective frequency window for vortex generation. Within the frequency window between 1.5 kHz and 3 kHz, the generated vortex is quite strong, and the vortex intensity indicator is higher than 80%. The intensity of both CW vortex and CCW vortex reaches a maximum at 2.5 kHz. When the actuation frequency is lower than 1 kHz or higher than 4 kHz, the vortex becomes very weak or even unable to occur in the chamber, and thus the intensity is below 15%. It is also found that the vortex direction stays unchanged when varying the applied frequency: CW vortex is generated only when Transducer A is actuated, and CCW vortex occurs only when Transducer B is actuated.

FIG. 4. Effect of actuation frequency on the generated vortex when Transducer A (solid line) or Transducer B (dashed line) of the PZT disk is actuated. The actuation voltage is 100 V and the flow rate is 10 ml/h in total. All the flow patterns are recorded when flows are fully developed at 40 s.

FIG. 5. Effect of actuation voltage on the generated vortex when Transducer A (solid line) or Transducer B (dashed line) of the PZT disk is actuated. The actuation frequency is 1.5 kHz and the flow rate is 10 ml/h in total. The inset images are recorded when flows are fully developed at 40 s.

A further investigation was conducted by varying the actuation voltage from 40 V to 100 V while keeping the frequency and flow rate as 1.5 kHz and 10 ml/h, respectively. The results when Transducer A (solid line) or Transducer B (dashed line) is actuated are presented in Fig. 5. The inset images were recorded when the flow patterns were fully developed at 40 s and the vortex intensity at this time was calculated. At 40 V, the fluids with fluorescent dye are slightly distorted in the chamber for both cases, indicating that the vortex is very weak. When the applied voltage is varied from 60 V to 100 V, a large vortex occurs inside the chamber and the vortex intensity increases greatly with the applied voltage while the vortex direction stays unchanged. At 100 V, the intensity of the CW vortex is as high as 90% as Transducer A is actuated and the intensity of the CCW vortex reaches 67% as Transducer B is actuated. It is also found that with increasing actuation voltages, the intensity indicator of the CW vortex is larger than that of the CCW vortex on the whole. Therefore, except for the vortex direction, the vortex intensity can also be tuned conveniently by varying the applied frequency and voltage. Ideally, the vortex intensity for Transducer A and Transducer B should be equal. However, due to the manufacturing challenges in such a small scale, the microfluidic device fabricated in our experiments is not perfectly symmetric about the mid-plane where the x-axis is located, and hence the configuration asymmetry results in the difference of the vortex intensity for CW and CCW vortices as shown in Fig. 5.

C. Mechanism of vortex generation and control

It has been demonstrated, in Secs. III A and III B that the vortices can be generated in the microfluidic chamber incorporated with actuators and the vortex directions can be controlled by varying the actuation conditions. Regarding the mechanism, we propose that the vortex generation in the present case is induced by the instability of the actuation-induced pulsatile flow through the sudden expansion part at the outlet of the chamber, while the vortex control is realized through the asymmetric flows in the chamber induced by the upper or lower transducers. Acoustic streaming is a second order nonlinear effect where the presence of an oscillatory flow generates steady mean vortical flows.^{22,23} However, the acoustic streaming relies on momentum transfer from the acoustic waves—standing waves or travelling waves—to the fluid.²³ In the present study, the typical actuation frequency for vortex generation is 1.5 kHz and the actuation pressure wavelength is about 1 m (taking the sound speed in water to be 1500 m/s). While the largest dimension of the microfluidic

chamber in our study is about 0.07 m, which is much smaller than the pressure wavelength. As a result, the actuation pressure is almost uniformly distributed in the microfluidic chamber and there is no acoustic wave in the microfluidic chamber. In other words, the fluid is incompressible inside the chamber in the present actuation frequencies, which indicates that acoustic streaming is not the mechanism of vortex generation in the present study.

It has been reported that the symmetric flow through a sudden expansion yields to a pair of stable and asymmetric vortices—a large vortex at one side and a small one at the other side, due to the instability of the flow at high Reynolds number (Re).^{24–32} Durst *et al.*²⁴ studied the flow in a symmetric expansion experimentally and numerically and showed that in a channel of expansion ratio (ER) equal to 3:1, the asymmetric vortices arose instead of a pair of symmetric vortices due to the symmetry-breaking bifurcation when Re was above 40.45. Alleborn *et al.*²⁶ demonstrated that, other than in a “sudden” expansion, the asymmetric vortices can also be formed in a “smooth” expansion and the critical Reynolds number for the flow instability increased with the degree of “smoothness” of the expansion. For example, for a 1:3 expansion ratio, the critical Reynolds number became 147 for an expansion of 10° semi-angle. Mizushima *et al.*^{28,29} investigated the transition of the flow through a rectangular chamber with ER equal to 3:1 and aspect ratio (AR) equal to 7:3. They found that the steady and symmetric flow became two vortices of unequal size when Re was larger than 47.7. Further investigations show that in the case of a large expansion ratio, the asymmetry of the two uneven-sized vortices in the flows through a sudden expansion or a rectangular chamber is greatly enhanced due to the reduction of the flow stability, as illustrated in Fig. 6.^{30–32} Revuelta³⁰ demonstrated that the asymmetric vortices in the flow through an expansion of large expansion ratios tended to appear for lower values of Reynolds number due to the momentum exchange between the incoming jet and the recirculating fluids. Dufresne *et al.*³² studied the flow fields in a rectangular shallow basin at high Reynolds number and found that in the chamber with $ER = 16 : 1$, the asymmetric flow had two vortices with distinct sizes: compared to the case of $ER = 3 : 1$, a larger vortex was formed inside the chamber and a smaller vortex was formed on the upper corner. In addition, it has been demonstrated that, even for a pulsatile flow through an expansion channel or a rectangular chamber, the transition to asymmetric vortices from a pair of symmetric vortices can also occur as a result of the flow instability when the Reynolds number exceeds the critical value.^{33,34}

In our study, the vibration of the PZT disk leads to the variation of the chamber volume. Since the flow rate at the inlets is maintained constant by the syringe pump, the outlet channel becomes the only passage for the incompressible fluids flowing into and out of the chamber corresponding

FIG. 6. Illustration of the steady flow through a sudden expansion or rectangular chamber with a large expansion ratio (ER). (a) The flow in a sudden expansion with a large expansion ratio at high Reynolds number. (b) The flow in a rectangular chamber with a large expansion ratio at high Reynolds number.

FIG. 7. Fluid flow through a suddenly expanded part with a very large expansion ratio (ER) in the outlet channel when the PZT disk is vibrating.

to the sucking and squeezing phase of the PZT disk. As shown in Fig. 7, the ratio of the diameter of circular chamber (16 mm) versus the width of the outlet channel (1 mm) is up to 16, which is a sudden expansion. Therefore, the vortex generation in our study is probably caused by the instability of the actuation-induced pulsatile flow through the sudden expansion when the fluids

The instability of the actuation-induced pulsatile flow through the sudden expansion ($ER=16:1$) at high Reynolds number ($Re=450$)

FIG. 8. (a) Fluid flow into and out of the chamber through a sudden expansion part (ER is the expansion ratio) of the outlet channel at high Reynolds number with the vibration of the PZT disk. (b) The variation of the cross-section mean velocity in the outlet channel with time in one cycle when Transducer A (solid line) or Transducer B (dashed line) is working.

are actuated into and out of the chamber through the outlet channel at high Reynolds number (Fig. 8(a)). In Fig. 7, it is also illustrated that the microfluidic chamber becomes asymmetric due to the asymmetric actuations, leading to the different vortex directions.

In order to further support our aforementioned assumption of the vortex generation in the present case, the transient velocity of the flow through the outlet of the chamber was measured to obtain the Reynolds number. A rectangular region, zone 1 (indicated in Fig. 1(d)), was selected to measure the time-dependent flow velocity in the outlet channel. The flow patterns of the fluids which were seeded by micron-sized particles were recorded by the high-speed camera and the images are analyzed through a Particle Image Velocimetry (PIV) software platform (DynamicStudio, Dantec Dynamics, Denmark) to obtain the flow velocities. In the experiment, the applied voltage and flow rate were 100 V and 10 ml/h, respectively. The sampling rate of the camera was 21 000 fps at the frequency of 1.5 kHz (14 records every cycle). The cross-section mean velocity $\bar{u}$ in the outlet channel is plotted with time in Fig. 8(b). It can be seen that when transducer A (solid line) or transducer B (dashed line) is actuated, the mean flow velocity fluctuates sinusoidally, indicating that the flow through the outlet is pulsatile corresponding to the vibration of the PZT disk. The peak velocity $\bar{u}_p$ of the pulsatile flow is up to 0.45 m/s, which is much greater than the mainstream velocity (0.01 m/s, denoted in Fig. 8(b)). This means that the inlet flow is negligible compared to the actuation-induced flow by the PZT disk. By taking $\bar{u}_p = 0.45$ m/s as the characteristic velocity, outlet width ($=1$ mm) as the characteristic dimension, and water as the working fluid, the Reynolds number is calculated to be 450, which is large enough for the flow instability in a sudden expansion of ER equal to 16 to generate vortices. To study the effect of the actuation frequency on the transient velocity in the outlet channel, we plot the peak-to-peak velocity in one cycle versus the actuation frequency in Fig. 9. It can be found that, within the frequency range between 1.5 kHz and 3 kHz, the amplitude of the pulsatile velocity is very large, about 0.4 m/s, while out of this frequency range, the velocity amplitude dramatically drops to 0.1 m/s. This frequency window of the velocity amplitude is in accordance with the frequency window for the vortex generation shown in Fig. 4. The vibration of the PZT disk leads to the variation of the chamber volume and the fluids are actuated into and out of the chamber through the outlet channel; due to the conservation of mass, the flow rate at the outlet is approximately equal to the change rate of the chamber volume because the inlet flow is negligible. In other words, the cross-section mean velocity at the outlet channel is proportional to the vibration velocity of the PZT disk, rather than the vibration displacement of the PZT disk.

FIG. 9. The effect of the actuation frequency on the amplitude of the pulsatile velocity in the outlet channel when Transducer A (solid line) or Transducer B (dashed line) is actuated.

Therefore, the frequency window for vortex generation or the flow velocity amplitude in the outlet channel is agreeable with the frequency window for the vibration velocity amplitude of the PZT disk rather than the vibration displacement amplitude of the PZT disk ([supplementary material S2](#)).

IV. CONCLUSIONS

In summary, we have presented a novel method for the generation and control of vortices in a microfluidic chamber with PZT actuations. The generated vortex is visualized by tracing fluorescent dyes in the fluid and recorded by a CCD camera. The results show that two regimes of vortices—CW (clockwise) vortex and CCW (counter-clockwise) vortex—can be formed inside a microfluidic chamber with actuations when the PZT disk is actuated at proper frequencies and voltages. The direction of the vortex can be shifted on-demand from clockwise to counterclockwise by simply switching between two different transducers and the vortex intensity can be tuned by the actuation frequency and voltage. To explore the mechanism of the vortex generation, PIV measurements have been conducted to obtain the flow velocity in the outlet channel. The results show that the flow in the outlet channel is pulsatile with the vibration of the PZT disk and the transient velocity is very large at proper actuation conditions, leading to a large Reynolds number. A frequency window of the velocity amplitude is identified between 1.5 kHz and 3 kHz, which is in accordance with the frequency range for the vortex generation. The vortex generation in the chamber with actuations is due to the flow instability when the fluids are driven through the sudden expansion part of the outlet channel at high Reynolds number with the vibration of the PZT disk. The reported method of vortex generation and control can be applied in flow control of microfluidic manipulations including mixing enhancement and distribution of microparticles and nanoparticles.

SUPPLEMENTARY MATERIAL

See [supplementary material S1](#) for the development of two regimes of vortices in the chamber with actuations and [S2](#) for the vibration measurement for the PZT disk.

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