EXPERIMENTAL INVESTIGATION ON PARAMETERS FOR THE CONTROL OF DROPLETS DYNAMICS

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Abstract

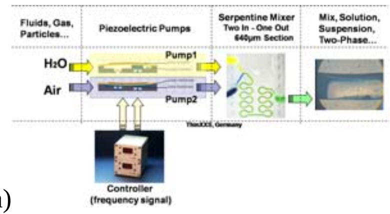
In this work temporal nonlinear dynamics in two-phase microfluidic phenomena are investigated. Time series representing the dynamics of two phase flow in an in vitro microfluidic serpentine mixer were captured using an optical magnification system and sensitive photodiodes in order to access to fast bubbles flow patterns in the time domain. Nonlinear analysis were performed: embedding space reconstruction, trajectories divergence curve, evaluation of the maximum Lyapunov exponent (λ_{max}) and d-infinite (d_∞). This work represents thus a first insight on temporal patterns related to two phase flow in microfluidics and it presents significant relationships between the control parameters under investigation and nonlinear indicators extracted from experimental time series.

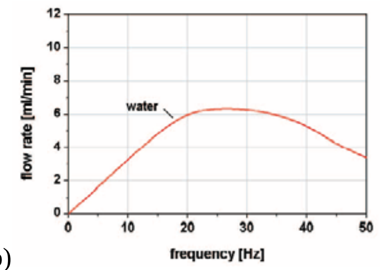
Key words

Two phase flow, Nonlinear time series analysis, Micro-mixer, Signal processing, Temporal chaos.

1 Introduction

In microfluidics, mixing depends mainly on molecular diffusion because microfluidic systems are restricted to laminar flow, so conventional mixing process are not applicable. There are several application field of microchannel based mixers: from reaction, gas absorption to emulsification, foaming etc . . . [Bruus, 2004] [Hessel et al., 2005]. The concept of nonlinearity and in particular of chaotic spatial dynamics in microfluidics has been widely explored in literature [Hessel et al., 2005] [Barbier et al., 2006] [Ottino et al., 2004] [Stremler et al., 2004] [Stroock et al., 2002] [Bringer et al., 2004] and significant applications have been explored especially in bio chemical analysis field [Bringer et al., 2004]. There are many ways to create nonlinear fluid motion in microfluidics such as electro-osmotic effect [Hessel et al., 2005], reorientations of the channel (passive mixers) [Stremler et al., 2004], droplets formation [Bringer et al., 2004], etc. In particular microscopic droplets and droplets formation and manipulation are often used for meter and mix small volume of fluids efficiently [Bringer et al., 2004] and for emulsions generation [Barbier et al., 2006]. Moreover droplet generation and manipulation using immiscible flow has the advantage to produce fast mixing in low cost device controlled by external flows. In this complex and fast evolving scenario microfluidic mixing had to be quantified and controlled. In order to follow this trend it is useful the application of nonlinear analysis methods to experimental time series representative of the microfluidic processes and intended as a sequences of observations representative of the physical process performed with a determinate measure function. The first issue to deal with is the non invasive extraction of optical information related to the temporal dynamics of the phenomena. In this work two phase flow (air-water) process flowing through a passive microfluidic serpentine was observed using a general purpose experimental workbench oriented to microfluidics through a photodiode-based sensing system that allows fast acquisition time. The successive step was the nonlinear analysis of the extracted time series. Important nonlinear parameters (embedding dimension, time delay, maximum Lyapunov exponent, d_j, d_∞) has been evaluated in the experimental data with the aim to characterize the complex temporal dynamics of droplets [Bucolo et al., 2008]. It is worth noticing that the analysis methods here presented are independent from the particular mechanism used to create motion and from the quality of the mixed fluids. The aim of this study is to investigate on the nonlinear dynamics of microfluidic two phase flow process and it represents the starting point toward deeper study of the effect of the input flow rate and frequency to temporal nonlinear dynamics of droplets.

(a) 

(b) 

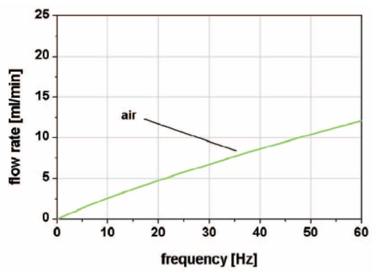
(c) 

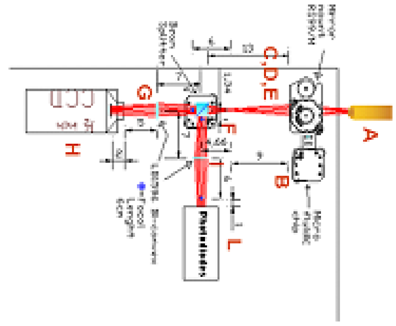
Figure 1. (a)Microfluidic Setup. (b)Flow rate versus pump frequencies for water. (c)Flow rate versus pump frequencies for air.

2 Experimental System

A general purpose design of an the experimental non-invasive workbench for microfluidic systems study has been already realized [Sapuppo et al., 2006] [Sapuppo et al., 2007] [Sapuppo et al., 2008]. The design of such system makes it suitable for both in vitro and in vivo experimental setup for application in the biomedical research field such as the study of microcirculation system and the analysis of micro-total-analysis systems (μTAS). Such system is made up of three main functional blocks: the microfluidic device, the sensing system and the monitoring-control system.

2.1 The microfluidic device

The serpentine snake mixer slide (SMS0104, Thinxxs), here considered, belongs to the class of passive snake mixer with two streams and has section of 640 μm and internal and external radius of curvatures of 280 μm and 920 μm. In the case here presented, air and water flow through the mixer obtaining a two-phase flow (Figure 1(a)). The input variables of the microfluidic mixer are water and air flow rates (Figure 1 (b),(c)). In the experimental setup the piezoelectric twin pumps (TPS1304, Thinxxs) are manually controlled through an electronic pump control (EDP0704, Thinxxs). Such control is actuated through the frequencies (fair, fwater) that set the actuator vibration of the piezo-driven diaphragm micropumps generating input flow rates for both air and water (Figure 1).



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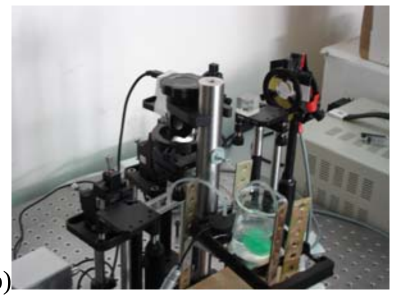
(b) 

(c) 

Figure 2. Electro optical system (a)Top view of the CAD design . (b)Experimental Setup . (c)Details of photodiodes.

2.2 Electro-optical system

The micro-scales of microfluidic devices requires an optical system for the extraction of parameter and variable involved in the microfluidic process. An optical system (Figure 2(a,b)) provides thus image magnification suitable for acquisition and processing. It has been set up with flexible discrete opto-meccanical components mounted on a breadboard in order to provide an optical path accessible at any point where the information needs to be acquired [Sapuppo et al., 2006] [Sapuppo et al., 2007] [Sapuppo et al., 2008].

2.3 Photodiode sensing system

The type of acquisition affects the monitoring system, since the information that need to be extracted and analyzed varies, according to such sensing equipment, from real-time signal processing [Sapuppo et al., 2007] to image processing [Sapuppo et al., 2006]. Two phododiodes, shown in Figure 2(c) (SLD-70BG2A, Silonex) have been chosen to capture light variation due to the droplets passage in the microchannel. They are planar photodiodes and measure 3.6 mm x 3.6 mm, with an active area of 9.8 mm^2. They are placed on the magnified image of the channel, on a axis parallel to the bubble flow (Figure 2(c)). An opportune conditioning circuit has been implemented in order to convert the photodiode current into amplified voltage signals. Also the photodiode board has been protected from out coming light. Parallel to photodiodes acquisition, an optical acquisition of images has been performed by a digital CCD camera (DCU223M Camera, Thorlabs) with a frame rate of about 35 frame/s. The magnification of the channel operated by the optical system is about 3. An experimental campaign has been carried out. It consists of 12 experiments obtained by varying the control frequencies of the pump control in a range between 5 Hz to 60 Hz with step of 5 Hz for water, with the air frequency fixed at 5 Hz . Such range of frequencies corresponds to a range of input flow rate of 0.2-3.5 ml/min for water and a fixed component of 2.3 ml/min for air (EDP0704, Thinxxs). During each experiment the pumps frequencies were chosen in the fixed range and then kept constant for the acquisition time of 15 s.

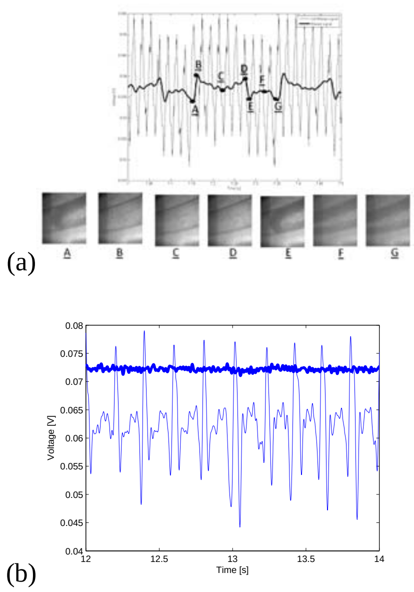


Figure 3. (a) Comparison between filtered (bold line) and not filtered signal (grey line) related to the experiment of water and air frequency at 5 Hz. The frames captured by the CCD camera during the same experiment matching the time series samples. (b) Comparison between signal representative of droplets dynamics water pumped at 25 Hz and air 5 Hz (thin line) and reference signal of water pumped at 10 Hz (bold line) in a time window of 2 sec.

3 Signal Processing

3.1 Pre-processing analysis and filtering

Following a spectral analysis all the photodiode signals have been filtered in order to reduce noise components due to environmental light and electrical interference signals due to the pump control. All the signals have been filtered with a low pass digital filter with cut off frequency of 60 Hz. In Figure 3(a) there is an example of filtered (bold black line) and not filtered signal (gray line). The parallel setup configuration (photodiodes and CCD camera) has been utilized in order to show the correspondence between frames and signals (Figure 3(a)) and to calculated the droplets dimensions showing the consistence of the acquired signals. The droplets height and width mean dimensions are 640 μm (channel width) and 1280 μm. Also a filtered signal obtained from the microfluidic two phase flow process (water 25 Hz and air frequency at 5 Hz) has been compared with a reference signal (water pumped at 10 Hz) (Figure 3(b)). Figure 3(b) makes clear how the mean value of the reference time series is higher compared to the times series representative of droplets flow dynamics, due to the fact that for all the time of the experiment the image remain bright lacking of the bubble shadow. This fact is demonstrated plotting the mean intensity value of the voltage signal over the proper water pump frequencies (Figure 4(a)).

3.2 Photodiode signals and droplets pattern

Four filtered photodiode signals have been compared to each other in a time windows of 2 s (Figure 4). These images show how the bubble passage is sensed by the photodiode and create a temporal pattern in the time series.

3.3 Nonlinear time series analysis

The nonlinear dynamic analysis has been carried out by means of the software TISEAN [Hegger et al., 1999]. The reconstructed states, methods for the extraction of important parameters that characterize the dynamics of the time series could be applied [Kantz et al., 2004]. The embedding dimension, time delay, Lyapunov exponents, trajectory divergence curve (d_j), d-infinite (d_∞), all characterize and quantify the dynamics of a nonlinear time series. In order to reconstruct the attractor from the experimental time series and to determine the embedding dimension m, the method of false nearest has been here used. Taking into account the delay τ, auto-mutual information has been used for the choice of the optimal value of the delay. The formula of the prediction error between very close trajectory was used to calculate the λ_{max}. Taking into account the divergence between trajectory, averaging N couples of trajectories starting from two nearby points belonging to the map F the mean distance between two trajectories after j iteration can be defined as (1):

$$d_j = \frac{1}{N}\sum_{i=1}^{N}|{y_i}^{(i)} - {y_i}'^{(i)}| \quad (1)$$

where the $|\cdot|$ operator denotes the Euclidean norm. The d_j asymptotic value (d_∞) is defined as [15]:

$$d_\infty = lim_{n\to\infty}\frac{1}{n}\sum_{j=1}^{n} d_j. \quad (2)$$

After a sufficiently large number of iterations, the folding process takes place to keep the trajectories bound in the phase space so the d can be considered a complete parameter because is sensitive to both stretching and folding mechanisms

4 Results and Comparison

The time series obtained from the experimental campaign were analyzed through nonlinear methodology (section 3.3), and the results are here shown and compared.

The parameters τ and d have been calculated for all the considered time series in order to reconstruct the phase spaces of the microfluidic process for different input frequencies. A value of the embedding dimension greater than 3 has been found for most of the experiments, so for obvious reasons a 3D representation has been here shown. The three dimensional view of the attractors of four time series is shown in Figure 5. Through these results it is possible to distinguish different dynamics of droplets flow as the input pump frequencies change, so the frequency of the input flow can be considered an important control parameter of the two phase flow dynamics. In order to have quantitative measures of the nonlinear temporal dynamics in experimental time series, the parameters d_∞ and λ_{max} have been calculated for each time series. The results are reported in Table 1 and from these results it is possible to verify that the considered parameters are sensitive to the changes in the pulsate input. Moreover, it is worth noticing that all the time series have a positive λ_{max}. The results in table 1 can be also discussed looking at the divergence curve d_j (Figure 6). Such curves confirm the dependence of the nonlinear behavior of the microfluidic time series from the pulsate input values. The initial slope, proportional to the λ_{max} and the asymptotic value d_∞ allows an intuitive comparison among the different dynamics so the input flow rate and frequencies of the carried fluid (water) determines significant dynamics of droplets.

Finally Figure **??** shows the relationship of two important nonlinear parameters as the largest Lyapunov exponents (λ_{max}) and d-infinite (d_∞) with the input water frequency. The decreasing trend as the carrier fluid (water) frequency increase indicates the reduction in the nonlinear features of the air bubbles flow. These results are important to identify and quantify the droplets flow patterns in order to find an experimental model and control law for the complex flow of two immiscible fluids in microfluidic channels using time pulsing forces (frequency and flow rate).

Table 1. Nonlinear parameters of the microfluidic two phase flow process

Water Frequency [Hz]	λ_{max}	log(d_∞)	Delay τ	Embedding Dmension m
5	3.33	-2.32	18	5
10	2.08	-2.14	10	4
15	1.98	-1.57	8	4
20	1.36	-1.77	9	5
25	1.94	-1.76	9	5
30	1.46	-1.53	9	4
35	1.89	-1.37	8	4
40	1.28	-1.54	8	4

5 Conclusion

Experimental methods have been used in this work to extract important two-phase (air/water) flow features for different input flow conditions (frequency, flow rate). In particular, time series were obtained as optical information through optical image magnification and standard photodiodes acquisition. A mathematical nonlinear analysis of experimental time series, representative of the microfluidic two phase flow process was then performed in various conditions, varying the input flow rate and frequencie of the carrier fluid (water) and keeping constant the frequency and flow rate of the other fluid (air). Qualitative and quantitative analysis has been performed on such experimental time series through the embedding space analysis and the extraction of significant nonlinear parameter such as the λ_{max} and d_∞. Such study has been performed in order to underline a relationship between the control parameters under investigation, as flow rate, fluid fraction, frequencies of the input pumps and the nonlinear parameters as λ_{max}, and d_∞. This leads to the concept that such parameters represent a sensitive control for the dynamics of the droplets in microfluidic phenomena. These results are also important for successive studies in droplets flow dynamic control for emulsion processes and mixing inside droplets.

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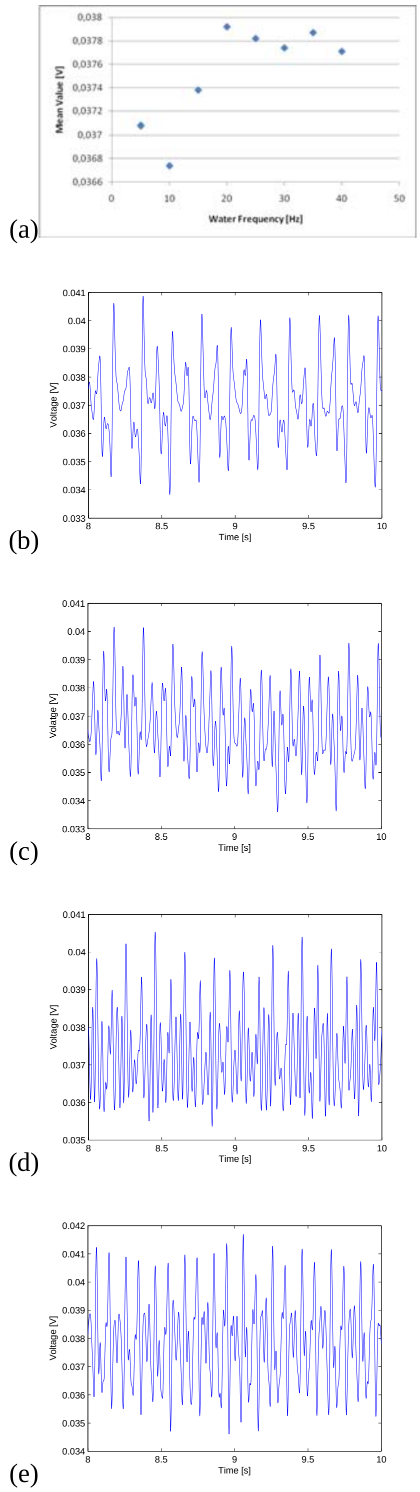
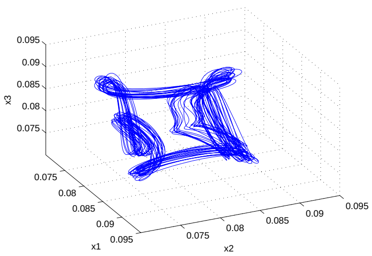


Figure 4. Signals in a time windows of 2 sec for air 5 Hz and varying the water frequency: (a)Photodiode time series mean values versus water frequencie (b) water 5 Hz (c) water 10 Hz (d) water 15 Hz (e) water 20 Hz.



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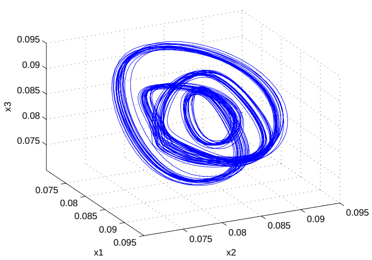

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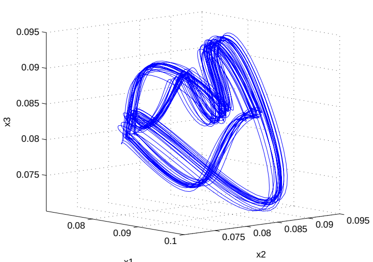

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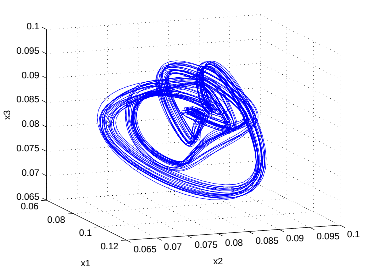

(d)

Figure 5. Reconstructed Phase Space of experimental time series from the two phase microfluidic flow process using air frequency 5Hz and varying the water frequency (a) 5 Hz. (b) 10 Hz. (c) 15 Hz. (d) 20 Hz.

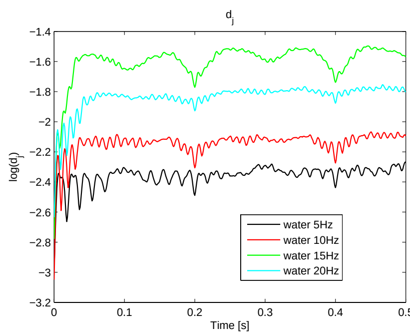

Figure 6. Logarithmic Divergence curve (d_j) for air frequency 5 Hz and varying the water frequency 5 Hz (black line), 10 Hz (red line), 15 Hz (green line), 20 Hz (cyan line).