STICK-SLIP BEHAVIOR OF LIQUID DROPLETS ON PILLAR-ARRAYED PDMS SURFACES

BY
XIAN WEI

THESIS
Submitted in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering In the Graduate College of the University of Illinois at Urbana-Champaign, 2014

Urbana, Illinois

Adviser:
Professor K. Jimmy Hsia
ABSTRACT

How the roughness of a solid impacts its wettability has been of long time interest. When a droplet moves on a rough surface, it usually undergoes a stick-slip motion. However, this phenomenon lacks a proper explanation with micro-level details and analysis. In this study, a series of experiments were conducted to monitor the contact line (CL) evolution and resistant force over time when moving droplets over micropillar patterned surfaces. MATLAB programs were developed to analyze both force and image data. Four parameters are found to have strong correlation with a droplet’s stick-slip behavior: pillar array spacing, droplet moving velocity, liquid surface tension, and droplet volume. Further study at the CL evolution images and force-time curve revealed that the stick-slip phenomenon is synchronized with pillar pinning and depinning at the CL. The evidence of liquid residues on pillars left by passing droplet supports the hypothesis of micro-capillary bridges formation and rupture, which could be a dominant mechanism governing the stick-slip behavior of moving droplets.
I would like to express my sincere gratitude to Prof. Jimmy Hsia for their patience and invaluable guidance. I would also like to extend the thanks to Prof. Sascha Hilgenfeldt, who constantly inspired me in my research. Thanks to my colleagues: Banglin Liu, Donghai Gai and Micheal Grigola for their help to this project. Thanks also to my family, friends and labmates, for their kind support through the challenging process of completing the requirements for my Master of Science degree.
# TABLE OF CONTENTS

CHAPTER 1:  Introduction ........................................................................................................ 1

CHAPTER 2:  Fundamentals .................................................................................................. 3
  2.1  Surface Science ........................................................................................................... 3
  2.2  Stick-Slip Phenomenon ............................................................................................... 7
  2.3  Fourier Transform ....................................................................................................... 8

CHAPTER 3:  Materials and Methods ................................................................................... 10
  3.1  Overview .................................................................................................................... 10
  3.2  Materials ...................................................................................................................... 10
  3.3  Test Setup and Test Plan ............................................................................................. 12
  3.4  Data Collection .......................................................................................................... 13

CHAPTER 4:  Results and Discussion .................................................................................... 17
  4.1  Force Measured during Dynamic Steady State (DSS) .................................................. 17
  4.2  Force Data Processing ................................................................................................. 22
  4.3  Contacted Interface in Dynamic Steady State (DSS) ................................................... 28

CHAPTER 5:  Stick-slip Phenomenon and the Contact line Evolution ................................. 32
  5.1  Image Processing ......................................................................................................... 32
  5.2  Displacement of Receding Pillars ............................................................................... 34
  5.3  Comparison of Displacement of Receding Contacted Pillars and Force Data... 35
  5.4  Discussion and Future Work ...................................................................................... 35

Reference .................................................................................................................................... 37

Appendix A: MATLAB Codes for Fourier Transform and Band-pass Filter ................. 39

Appendix B: Matlab Codes for Slope Analysis ....................................................................... 42
CHAPTER 1: INTRODUCTION

When liquid is brought in contact with solid, things become very interesting. Depending on the interaction force, liquid can be either sticky or unsticky. Sometimes we prefer liquid to have firm contact with solid. For example, we like to have soil get wet easily so that it will preserve water in rainy days; we wish the paint be adhesive so that it won’t fall. However, this is not always the case. It must annoying when you get rains stick to your windshield while your wiper happens to go on strike, not to mention the fresh coffee stain on your newly bought dress.

Controlling the wettability of solid materials became an interesting issue and a long time classic. Young-Dupre equation developed in 1800s relates the surface tension between solid, liquid and gas phases; Wenzel model developed in 1900s describes wetting on homogeneous surfaces. Recent decades with the development of the semiconductor industry, it is possible to observe and even manipulate liquid-solid interaction at micro/nano level. In 1970s, Wilhelm Barthlott first used high scanning electron microscopy to image plant surfaces and discovered the micro- and nano-structures on hydrophobic plant surfaces like lotus leave[1]. The discovery of lotus effect initiated a boost in research on roughness modifying surface wetting properties. In 1990s, researchers at Kao Corporation in Japan constructed solid materials with controlled micro-structure, achieving extreme anti-wetting property (contact angle ~180°).

The dynamics of liquid droplets moving over micro structured solid surfaces has always been of great interest to surface scientists, but has lacked detailed study at the level of the micro-scale pattern. Three major challenges lie in this issue:
1. Acquisition of the shape evolution of the sessile drop;

2. Measuring the force required to move the sessile drop over certain surface;

3. Interpretation of the data and understanding the underlying mechanisms.

A popular way to study dynamics of droplets in the past was to use an inclined plane and study droplet’s advancing and receding angles when the droplets were unpinned. Recently, some techniques have been developed to study the contact line of moving droplets, such as optical microscopy, laser scanning confocal microscopy, and ESEM ([2]–[7]). As for force measurement, Pilat et al. has developed a drop adhesion force instrument (DAFI) to measure the force required to move a droplet [8]; Thanh-Vinh et al. has built a MEMS two axis force sensor array to measure the force of a sliding droplet[9].

In 2011, Li innovatively built a set up to record both the contacted area and force data simultaneously [10]. He used a fluorescent microscope to take videos of the contact area of a fluorescence-dyed moving droplet, meanwhile adhering a force sensor to the droplet. By continuing monitoring a moving droplet while also recording the force to keep it moving at a constant speed, Li discovered that the force value is always related to the contact area. Li also discovered that the force data presented a stick-slip behavior when the droplet is moving on pillar-arrayed PDMS substrate[10]. However, he did not provide a full explanation to this phenomenon.

The focus of this study is to analyze the force data collected from Li’s set-up, especially the dynamic steady state. Further, this study tries to correlate the image data with the force data in order to explain the stick-slip phenomenon.
CHAPTER 2: FUNDAMENTALS

2.1 Surface Science

Surface science is the study of phenomena people have observed at the interface of two phases, such as solid-liquid, solid-gas and liquid-gas interfaces. This is a broad subject that covers many topics, with five that are closely related to this study:

- Surface energy
- Contact angle and wetting modes
- Behavior of liquid droplets on pillar-patterned solid surfaces
- Micro-capillary bridges between liquid droplet and pillars

Surface Energy

Surface energy is the quantity that denotes the energy required when a new surface is created. This reflects the cohesion of the underlying condensed phase. In a liquid, the surface energy and the surface tension are identical. It is also a concept to describe the interaction between molecules of different phase.

Surface energy is an important concept to describe contact line behavior. At a three-phase contact line, it is the surface energy of liquid-vapor, solid-air, and liquid-solid that matters. They determine not only the value of contact angle, but also the shape of the contact line. In other words, contact angle and shape of the contact line reflect the corresponding interfacial energy.

Contact Angle and Wetting Modes
Contact angle is the angle of a liquid/vapor interface when it meets with solid surface (as shown in Figure 1). For any point at a static contact line, the surface forces must be balanced:

\[ \gamma_{LV} \cdot \cos \theta + \gamma_{LS} = \gamma_{SV} \]

\[ \cos \theta = \frac{\gamma_{SV} - \gamma_{LS}}{\gamma_{LV}} \]

Figure 1. Illustration of contact angle

Contact angle is a parameter to define the wettability of a certain solid surface.

Table 1. Contact angle and surface wettability

<table>
<thead>
<tr>
<th>Contact angle</th>
<th>Degree of wetting</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \theta = 0^\circ )</td>
<td>Perfect wetting</td>
</tr>
<tr>
<td>( 0^\circ &lt; \theta &lt; 90^\circ )</td>
<td>High wettability</td>
</tr>
<tr>
<td>( 90^\circ &lt; \theta &lt; 180^\circ )</td>
<td>Low wettability</td>
</tr>
<tr>
<td>( \theta = 180^\circ )</td>
<td>Perfectly non-wetting</td>
</tr>
</tbody>
</table>

Figure 2. Illustration of contact angle and surface wettability
Behavior of Liquid Droplets on Pillar-Patterned Solid Surfaces

When a liquid droplet gets in contact with a pillar-arrayed patterned solid surface, the liquid either penetrates into the gaps between pillars or stays on top of the pillars leaving air cushion between pillars. The former is called Wenzel State, while the latter is called Cassie-Baxter State, or Fakir State, as shown in Figure 3. A liquid droplet in the Fakir State is also called a Fakir droplet. Whether a droplet would be in a Wenzel State or Cassie-Baxter State depends on many factors, including the surface energy of the liquid, the surface energy of the solid, the height/shape/top area of the pillar, etc.

Micro-Capillary Bridge between Liquid Droplet and Pillars

Micro-capillary bridge formation and break-up can occur when a fakir droplet moves and detaches from pillars, leading to liquid deposition on the pillars [11][7][9][12]. It was shown that the volume of liquid residue on a pillar depends on the liquid-solid interaction properties, the stretching velocity of the detached liquid bridge[13]
Sessile Drop Oscillations

For surface tension restored oscillations, the ordinary frequency takes the form of:

\[
f_{ml} = \frac{1}{2\pi} \sqrt{\frac{\gamma}{\rho V \lambda_{ml}}}
\]

Equation 1

\(f_{ml}\) ---- Oscillation frequency (in Hz) of an oscillation mode of degree \(l\) and order \(m\);

\(\gamma\) ---- Surface energy of the liquid;

\(\rho\) ---- Density of the liquid;

\(V\) ---- Volume of the liquid droplet;

\(\lambda_{ml}\)---- Eigenvalue of a surface tension based drop oscillation mode of degree \(l\) and order \(m\).

Specifically, when a sessile drop moves on a solid, the oscillation mode is of order \(m = 1\), and degree \(l = 1\), as shown in Figure 5.
Figure 5. Oscillation of mode order 1 and degree 1. Diagram is taken from Fig 7 of Chiba et al. 28 [14]

Eigenvalue $\lambda_{11}$ changes with different contact angles $\theta$. The relationship between $\lambda_{11}$ and $\theta$ is extensively studied, as shown in Figure 6.

Figure 6 Eigenvalues versus contact angle for mode 1-1 oscillation of sessile drops.
Diagram taken from Milne, et al. [15]

2.2 Stick-Slip Phenomenon

Stick-slip phenomenon is the spontaneous jerking motion that occurred when two objects are sliding over each other. Usually, stick-slip phenomenon would involve surface alternating between sticking to each other and sliding over each other, i.e. one surface is heterogeneous to another. This motion usually lead to in triangle/sawtooth liked force measurement.
If a droplet moves on a surface that is heterogeneous hydrophilic/hydrophobic periodic patterned, the corresponding adhesion force-time measurement will behave like triangle signal. Characteristic parameters of a triangle signal include but not limit to: period/frequency, rising interval, slope, and amplitude.

2.3 Fourier Transform

Fourier transform a mathematical tool to transform data from the time domain to the frequency domain. Inverse Fourier transform is the one that transform data from the frequency domain to the time domain. This is useful when dealing with periodically data like audio, image, etc. Data presented in the frequency domain will make it possible to identify signal components and noise. By strengthening target data component and weakening unwanted data components, followed by an Inverse Fourier Transform, it is possible to isolate data components from the original signal.

A Fourier series is an expansion of a periodic function \( f(t) \) in terms of an infinite sum of \( sines \) and \( cosines \). A typical expression is:

\[
f(t) = \frac{1}{2} a_0 + \sum_{n=1}^{\infty} a_n \cos(nt) + \sum_{n=1}^{\infty} b_n \sin(nt)\]

Equation 2

For an asymmetric triangle wave:

\[
a_0 = 0 \\
a_n = 0 \\
b_n = -2(-1)^n \frac{m^2}{n^2(m-1)^2 \pi^2} \sin \left[ \frac{n(m-1)\pi}{m} \right]
\]
Figure 7 illustration of Fourier series of triangle waves [16]
CHAPTER 3: MATERIALS AND METHODS

3.1 Overview

The study was designed to understand the droplet’s stick-slip behavior. Specifically, the study intends to examine six major physical factors:

1. Pillar size
2. Pillar-array spacing
3. Droplet moving velocity
4. Liquid type (surface energy)
5. Volume of the liquid droplet

For the six above physical variables, 1-3 are related to substrate design; 4 is controlled by the experiment condition; and 5-6 are related to the droplet’s intrinsic property.

To achieve this goal, four sets of experiments were designed to examine the role of each of the six physical variables in droplet’s stick-slip phenomenon.

3.2 Materials

Substrate

Two sets of substrates were prepared for this study, labeled as (1) and (2), with different pillar size and spacing. The designed pillar size and spacing are:

<table>
<thead>
<tr>
<th>Substrate #</th>
<th>Pillar type</th>
<th>Lattice Type</th>
<th>Pillar diameter (µm)</th>
<th>Lattice Parameter (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>Circular</td>
<td>Square</td>
<td>30</td>
<td>77</td>
</tr>
<tr>
<td>(2)</td>
<td>Circular</td>
<td>Square</td>
<td>50</td>
<td>88</td>
</tr>
</tbody>
</table>
The substrates are made of PDMS (polydimethylsiloxane, Sylgard184), which is a transparent hydrophobic material, through the method of molding.

First, SU-8 molds for pillar-arrayed substrates were fabricated using standard soft lithography techniques as following procedures:

1. Preparing material: 4 inch wafer; SU-8 (50) as photo-resist; SU-8 developer; photolithography mask;
2. Clean the wafer with acetone; then IPA; then DI water; then IPA; then dry with nitrogen.
3. Hard bake the wafer at 110°C for 1 min;
4. Spin-coat the SU-8 photoresist onto the wafer, with spin rate 3500 rpm for 40s;
5. Soft bake the coated wafer at 65°C for 15

Then, with the molds ready, PDMS substrates can be prepared in following method:

1. Wrap the wafer with wax rod.
2. Mix the PDMS base and cross-linker at 10:1 by weight. Stir for 5 min, then vacuum the mixture until all bubbles vanish.
3. Pour the PDMS mixture to the mold until a preferred thickness (usually about 5mm). Vacuum the mixture again to get rid of bubbles.
4. Put the mold containing the PDMS mixture on a leveled horizontal platform. Wait for two days for curing.
5. De-mold the PDMS.
**Liquid**

Two kinds of liquid are used in this study: one is pure DI water, and the other is DI water mixed with glycerol. This allows us to examine the effect of liquid surface tension on the stick-slip phenomenon.

Droplets of size 2μL, 4μL, 6μL and 10μL were used in the experiment.

In order to identify the droplet-solid interface, a fluorescent dye – fluorescein disodium \( C_{20}H_{10}Na_2O_5 \) (purchased from ACROS) is mixed with the liquid. Concentration of the dye is 6.44ppm.

**3.3 Test Setup and Test Plan**

This study followed similar set-up scheme in Li’s work, as shown in Figure 8 [10].

PDMS substrate is put on the surface of a stage, which can be moved horizontally with a controlled velocity. The liquid droplet (illustrated as the green ball in Figure 8) is placed on top of the substrate. A force sensor (FT-S1000, Femto-Tools) with tip modified by PDMS sphere is placed in contact with the liquid droplet; a microscope with a high speed camera is placed under the transparent PDMS substrate and stage. Both the force sensor and camera are connected to a lab computer to get their readings and recordings.
Figure 8. Scheme of the experiment set-up. Photo taken from Li’s dissertation[10].

Four sets of continuous experiments were conducted. The experiment conditions are illustrated in Table 3.

To achieve the goal of understanding the droplet’s stick-slip behavior, four sets of experiments were designed as shown in Table 3;

<table>
<thead>
<tr>
<th>#</th>
<th>Substrate*</th>
<th>Droplet Type</th>
<th>Volume (µL)</th>
<th>Speed (µm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(1)</td>
<td>1:1 DI water &amp; Glycerol + Fluorescent Dye</td>
<td>2</td>
<td>80</td>
</tr>
<tr>
<td>2</td>
<td>(1)</td>
<td>1:1 DI water &amp; Glycerol + Fluorescent Dye</td>
<td>4</td>
<td>80</td>
</tr>
<tr>
<td>3</td>
<td>(2)</td>
<td>1:1 DI water &amp; Glycerol + Fluorescent Dye</td>
<td>6</td>
<td>80</td>
</tr>
<tr>
<td>4</td>
<td>(2)</td>
<td>DI water + Fluorescent Dye</td>
<td>10</td>
<td>511</td>
</tr>
</tbody>
</table>

*Actual specifications of substrate type (1) and (2) were measured and defined in the following session, 3.4.

3.4 Data Collection

Substrate dimension:

Dimensions of PDMS substrates with micropillar arrays are specified in Table 4.

<table>
<thead>
<tr>
<th>Substrate #</th>
<th>Pillar type</th>
<th>Lattice Type</th>
<th>Pillar Parameter (µm)</th>
<th>Lattice Parameter (µm)</th>
<th>Area Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>Circular</td>
<td>Square</td>
<td>28.0</td>
<td>77.1</td>
<td>0.10</td>
</tr>
<tr>
<td>(2)</td>
<td>Circular</td>
<td>Square</td>
<td>43.2</td>
<td>88.0</td>
<td>0.19</td>
</tr>
</tbody>
</table>
Figure 9. Illustration of micropillars on the PDMS substrate. Picture was taken using Zeta 3D optical profiler.

Liquid contact angle

Contact angles were measured using a goniometer (KSV CAM200).

Table 5. Contact angles of liquids on two substrates

<table>
<thead>
<tr>
<th>Substrate #</th>
<th>Liquid</th>
<th>Contact angle (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>DI water</td>
<td>142.9</td>
</tr>
<tr>
<td>(1)</td>
<td>water-glycerol mixture</td>
<td>143.11</td>
</tr>
<tr>
<td>(2)</td>
<td>DI water</td>
<td>140.2</td>
</tr>
<tr>
<td>(2)</td>
<td>water-glycerol mixture</td>
<td>139.8</td>
</tr>
</tbody>
</table>

Monitoring droplet-substrate interface

Videos with certain frame rate are captured by the microscope with high-speed camera under the stage.

Figure 10 is one frame from the video illustrating the bottom view of a droplet moving on a pillar-arrayed PDMS substrate. The circular contour is the projection of the droplet, while the inner darker region with a bright edge represents the contact interface of liquid and solid substrate. The bright edge of this region is identified as the contact line.
Monitoring force data

Force data with certain sampling rate is captured by the software came with the force sensor (FT-S1000, Femto-Tools).

Figure 11 is a typical force data of moving a droplet on a micropatterned substrate; data was captured by the force sensor (FT-S1000, Femto-Tools)
Figure 11 A typical force data of moving a droplet on a micropatterned substrate; data was captured by the force sensor (FT-S1000, Femto-Tools)
CHAPTER 4: RESULTS AND DISCUSSION

4.1 Force Measured during Dynamic Steady State (DSS)

Figure 12 is a typical measured force-time curve. The force data can be categorized into four zones: adhesion; force increase; force decrease and dynamic steady state (DSS). The study here focuses on the last one, i.e., DSS.

![Figure 12. A typical measured force-time data](image)

As discussed in 2.2, for a stick-slip time-series data, three parameters are very important: period/frequency, slope, amplitude and rising interval. Period/frequency information can be obtained by Fourier transform the force data from the time domain to the frequency domain. However, to statistically extract information on slope, amplitude and rising interval, clearly filtering out the noise is necessary, which requires identifying the unwanted signal components in the frequency domain.
After acquiring the original DSS force-time data, Table 6 shows the original DSS force data in both time domain and frequency domain. Several peaks can be identified in the frequency domain figures.

The force sensor in this experiment measured not only the force representing stick-slip phenomenon, but also noises such as droplet vibration, stage vibration, etc. For each measurement, it is necessary to have a band-pass filter based on understanding the force data in the frequency domain. Data in the time domain can be transformed into the frequency domain through Fourier Transform as noted in 2.3. The transformation was performed with a self-written MATLAB program. The corresponding MATLAB codes can be found in Appendix A.

**Table 6 DSS force results in both time domain and frequency domain. The figures on the left column, marked as 1a, 2a, 3a, 4a, are DSS force in time domain for experiment 1-4; the figures on the right column, marked as 1b, 2b, 3b, 4b, are DSS force in frequency domain for experiment 1-4.**

<table>
<thead>
<tr>
<th>#</th>
<th>DSS Force in Time Domain</th>
<th>DSS Force in Frequency Domain</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><img src="signal.png" alt="Signal after cut" /></td>
<td><img src="spectrogram.png" alt="Single-Sided Amplitude Spectrum of signal" /></td>
</tr>
</tbody>
</table>

1a

1b
<table>
<thead>
<tr>
<th>#</th>
<th>DSS Force in Time Domain</th>
<th>DSS Force in Frequency Domain</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td><img src="image2a.png" alt="Image 2a" /></td>
<td><img src="image2b.png" alt="Image 2b" /></td>
</tr>
<tr>
<td>3</td>
<td><img src="image3a.png" alt="Image 3a" /></td>
<td><img src="image3b.png" alt="Image 3b" /></td>
</tr>
<tr>
<td>4</td>
<td><img src="image4a.png" alt="Image 4a" /></td>
<td><img src="image4b.png" alt="Image 4b" /></td>
</tr>
</tbody>
</table>
Figure 13 is a zoom in for a typical frequency domain transformed from force-time data acquired from the experiments. It is obvious to notice that there are three main peaks in the frequency domain.

It is easy to identify that peak 2-5 represent the stick-slip behavior since the frequency of peak 3-5 each is a multiple of peak 2. Peak 2 is the fundamental peak of the data in the frequency domain.

We hypothesized that peak 1 is related to drifting of the droplet due to small misalignment of the substrate on the experiment platform. This hypothesis has been confirmed by a quick test experiment showing change in peak 1 when changing the alignment of the sample. Signal that represents peak 1 is called drifting signal.

We also hypothesized peak 6 is caused by the droplet oscillation. To confirm this point, we first developed theoretical predictions of the frequencies of the droplet oscillation in our current experiment set-ups, and then we compare the predicted frequency with the measured frequency. Signal that represents peak 6 is called oscillation signal.
Both the drifting signal and oscillation signal are considered unrelated to the stick-slip phenomenon, and should be filtered out once confirmed.

*Theoretical Prediction of Frequencies of Droplet Oscillations.*

From Figure 6 in 2.1 we can learn that, for a contact angle of \( \sim 140^\circ \), \( \lambda_{11} \approx 0.351 \). Frequencies of droplets used in current experiment set-up can be calculated according to Equation 1 in 2.5 as shown in Table 7.

<table>
<thead>
<tr>
<th>#</th>
<th>Liquid</th>
<th>Surface Energy (N/m)</th>
<th>Density (kg/m(^3))</th>
<th>Volume (µL)</th>
<th>( \lambda_{11} )</th>
<th>Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Water-glycerol mixture</td>
<td>0.067</td>
<td>1260</td>
<td>2</td>
<td>0.351</td>
<td>43.55</td>
</tr>
<tr>
<td>2</td>
<td>Water-glycerol mixture</td>
<td>0.067</td>
<td>1260</td>
<td>4</td>
<td>0.351</td>
<td>30.80</td>
</tr>
<tr>
<td>3</td>
<td>Water-glycerol mixture</td>
<td>0.067</td>
<td>1260</td>
<td>6</td>
<td>0.351</td>
<td>25.14</td>
</tr>
<tr>
<td>4</td>
<td>DI water</td>
<td>0.072</td>
<td>1000</td>
<td>10</td>
<td>0.351</td>
<td>22.67</td>
</tr>
</tbody>
</table>

Table 8 compares the predicted oscillation frequencies and the measured frequencies identified from method described previously. The measured frequencies are about 6-9 Hz larger than the predicted frequencies, since they fell in the same range. Given that the droplet is moving on the substrate which would lead to a change in contact angles, it is reasonable to assume the measured frequency to be the droplet's oscillation frequency.

<table>
<thead>
<tr>
<th>#</th>
<th>Predicted Frequency (Hz)</th>
<th>Measured Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>43.55</td>
<td>52</td>
</tr>
<tr>
<td>2</td>
<td>30.80</td>
<td>38</td>
</tr>
<tr>
<td>3</td>
<td>25.14</td>
<td>31</td>
</tr>
<tr>
<td>4</td>
<td>22.67</td>
<td>30</td>
</tr>
</tbody>
</table>
4.2 Force Data Processing

Filtering the Force Data

Band-pass filters can be created after identifying drifting signal and oscillation signal for each experiment.

A self-written MATLAB program has developed to filter the signal and identify the peak and valley in each period in DSS for a given force data. The corresponding MATLAB codes can be found in Appendix A & B. Results are presented in Table 9

Table 9 Original DSS force data and filtered DSS force data, with peak and valley identified. Peaks are marked with red circles, and valleys are marked with green circles. The figures on the left column, marked as 1a, 2a, 3a, 4a, are original DSS force data for experiment 1-4; the figures on the right column, marked as 1b, 2b, 3b, 4b, are filtered DSS force for experiment 1-4.

<table>
<thead>
<tr>
<th>#</th>
<th>Original DSS Force Data</th>
<th>Filtered DSS Force Data</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1</strong></td>
<td><img src="image1" alt="Original DSS Force Data" /></td>
<td><img src="image2" alt="Filtered DSS Force Data" /></td>
</tr>
<tr>
<td><strong>2</strong></td>
<td><img src="image3" alt="Original DSS Force Data" /></td>
<td><img src="image4" alt="Filtered DSS Force Data" /></td>
</tr>
</tbody>
</table>
Table 9 (cont.)

<table>
<thead>
<tr>
<th>#</th>
<th>Original DSS Force Data</th>
<th>Filtered DSS Force Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td><img src="image1.png" alt="Image 1" /></td>
<td><img src="image2.png" alt="Image 2" /></td>
</tr>
<tr>
<td>4</td>
<td><img src="image3.png" alt="Image 3" /></td>
<td><img src="image4.png" alt="Image 4" /></td>
</tr>
</tbody>
</table>

**Rising Rate, Amplitude, and Rising Interval**

According to 2.2, parameters that are closely related to stick-slip phenomenon are period, rising interval, amplitude and rising rate. These parameters are defined and calculated in the following way:

**Main frequency**: identified usually as the highest peak in the DSS force in the frequency domain.
**Rising Rate:** the slope of the force data while the force is climbing, with CL pinned at the receding edge. This is calculated from least square fitting for force data between valley and neighboring peak in each cycle.

**Rising interval:** the time required for the force data to climb from valley to peak, denoted as $T_s$ here. During this interval, the contact line (CL) remains pinned to the pillar tops.

**Amplitude:** the difference in the force data between the valley value and the neighboring peak value, denoted as $A$ here. It marks the force required for CL to migrate from one column of pillars to the next neighboring column.

Figure 14 is an illustration of the parameters mentioned above. A self-written MATLAB program was developed to capture these DSS characteristic parameters.

*Figure 14. A zoom-in picture of the force-time signal in DSS*
For each experiment design, there are more than one period in the DSS, this allowed us to calculate for the mean value and standard deviation (SD) for each parameter in each experiment. All the results are summarized and shown in Table 10.

Table 10. Summary of the results

<table>
<thead>
<tr>
<th>#</th>
<th>Main Frequency (Hz)</th>
<th>Rising Rate (µN/s)</th>
<th>Amplitude (µN)</th>
<th>Rising Interval (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.0254</td>
<td>6.631±0.529</td>
<td>5.809±0.796</td>
<td>0.830±0.067</td>
</tr>
<tr>
<td>2</td>
<td>1.0254</td>
<td>5.603±0.279</td>
<td>4.116±0.225</td>
<td>0.720±0.044</td>
</tr>
<tr>
<td>3</td>
<td>1.0254</td>
<td>5.944±0.279</td>
<td>3.041±0.281</td>
<td>0.473±0.052</td>
</tr>
<tr>
<td>4</td>
<td>5.9814</td>
<td>40.31±7.89</td>
<td>6.22±0.76</td>
<td>0.123±0.004</td>
</tr>
</tbody>
</table>

**Main Frequency**

We hypothesized that the main frequency is determined by the spacing of the pillar-arrayed pattern of the substrate. Specifically, we assumed that in each period calculated from the main frequency, the droplet would travel a distance that is about the length of one spacing, as illustrated in Equation 3:

\[
\frac{\text{Speed}}{\text{Main Frequency}} \approx \text{Sample’s designed spacing} \quad \text{Equation 3}
\]

Table 11 calculates in each experiment the distance traveled in one cycle, and compare it with the corresponding spacing of the substrate. It is interesting to notice that, independent from the liquid type, droplet volume, pillar size and velocity, the values of these two parameters matches very well. This implies that the substrate’s designed spacing controls the force data pattern: the larger the spacing is, the longer a period it would require. Furthermore, this suggests that it is possible to use the droplet moving method to determine the spacing of a pillar-arrayed substrate.
Table 11. Main frequencies of experiments 1-4

<table>
<thead>
<tr>
<th>#</th>
<th>Main Frequency (Hz)</th>
<th>Speed (µm/s)</th>
<th>Distance traveled in one cycle (µm)</th>
<th>Spacing (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.0254</td>
<td>80</td>
<td>78.01833</td>
<td>77.1</td>
</tr>
<tr>
<td>2</td>
<td>1.0254</td>
<td>80</td>
<td>78.01833</td>
<td>77.1</td>
</tr>
<tr>
<td>3</td>
<td>1.0254</td>
<td>80</td>
<td>78.01833</td>
<td>77.1</td>
</tr>
<tr>
<td>4</td>
<td>5.9814</td>
<td>511</td>
<td>85.4315</td>
<td>88.0</td>
</tr>
</tbody>
</table>

*Rising Rate*

We would like to correlate the rising rate with the corresponding variables mentioned in 3.1 to see what parameters would have an influence on it.

Experiment #1, #2, #3 has the same experiment setup except for droplet volume. The rising rates calculated from the three experiments are similar. Experiment #4 shows a much larger rising rate compare to the experiment #1, #2, #3. However, if you look at rising rate from spatial perspective ---- rather than time perspective ---- by having the rising rate divided by the corresponding speed, the stiffness are similar. Therefore, it can be concluded that stiffness in the current experiment set up measured ranges from 70µN/µm to 83 µN/um, independent of at from droplet size and speed.

Table 12. Rising rates of experiments 1-4

<table>
<thead>
<tr>
<th>#</th>
<th>Droplet volume (µL)</th>
<th>Rising Rate (µN/s)</th>
<th>Speed (µm/s)</th>
<th>Stiffness (µN/µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>6.631±0.529</td>
<td>80</td>
<td>82.89±6.61</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>5.603±0.279</td>
<td>80</td>
<td>70.04±3.49</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>5.944±0.279</td>
<td>80</td>
<td>74.30±3.49</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>40.31±7.89</td>
<td>511</td>
<td>78.88±15.44</td>
</tr>
</tbody>
</table>

*Amplitude*

From Table 13, it can be concluded that amplitudes decrease with increasing droplet size.
Table 13. Droplet Size & Amplitudes of experiments 1-3

<table>
<thead>
<tr>
<th>#</th>
<th>Droplet volume (µL)</th>
<th>Amplitude (µN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>5.809±0.796</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>4.116±0.225</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>3.041±0.281</td>
</tr>
</tbody>
</table>

**Rising Interval**

From Table 14, it can be concluded that rising intervals decrease as droplet size increases.

Table 14. Rising intervals of experiments 1-3

<table>
<thead>
<tr>
<th>#</th>
<th>Droplet Volume (µL)</th>
<th>Rising Interval (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>0.830±0.067</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>0.720±0.044</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>0.473±0.052</td>
</tr>
</tbody>
</table>

It is easy to understand why amplitude behaves similarly to rising interval since amplitude is roughly rising rate multiplied by rising interval, considering that the rising rates for varying droplet volumes are about the same. What surprise us is that, the rising rate decrease as droplet gets larger.

Assuming that the time when force starts to decrease is also a time when major pillar depinning event initiates. One conjecture about this is that, the necessary condition to initiate depinning events is that the droplet must be so much deformed that at the advancing edge it has touched the next neighboring column of pillars. The smaller the droplet is, the larger the deformation is required.
4.3 Contacted Interface in Dynamic Steady State (DSS)

When a droplet moves on a solid surface, the three-phase contact line serves as pinning-depinning sites to produce local deformation, leading to contact angle hysteresis. Therefore, understanding the contact line evolution is a key to investigate the stick-slip behavior of droplets moving on micropatterned surfaces.

In this study, liquid droplet stands on the pillars in Fakir State, making it hard to define and recognize the actual contact line. However, it is possible to capture all the contacted pillars at the solid-liquid interface. Specifically, we are interested in those at the edge. Contacted pillars at the edge will serve as representatives of the contact line in this study. According to Pilat et. al [8], the receding contact line would be considered to contribute more in droplet’s moving on solid surfaces. Therefore, we focused on receding contacted pillars only in this study.

Evolution of receding contacted pillars

To move from one pillar to another along the advancing direction, the receding contact line had to depin from one pillar and jump to the next to get pinned. This depinning-pinning transition is found to help to overcome the energy barrier in Cassie-Wenzel wetting transitions [17].

The periods of depining-pinning transition for the receding pillars are the same and equal to the global period calculated from spacing over velocity. However, their phase varies one from another depending from their locations.
Similar to Dufour et. al [11], in this study the receding contacted pillars in DSS in one image frame are categorized into three zones: Primary Zone; Secondary Zone; Transitional Zone.

How the pillars were categorized does not depend on their location, but their corresponding point-in-time in force-time data, as shown in Table 15. This is identifiable by synchronizing the video with force-time curve. Figure 15 is an illustration of receding pillars in different zones.

**Table 15. Receding edge pillar categories**

<table>
<thead>
<tr>
<th>Pillar Zones</th>
<th>Where is the zone?</th>
<th>When does droplet depin from these pillars?</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Primary Zone</strong></td>
<td>In the middle, perpendicular to the moving direction</td>
<td>Falling interval</td>
</tr>
<tr>
<td><strong>Secondary Zone</strong></td>
<td>At top and bottom of the trailing edge</td>
<td>Falling interval</td>
</tr>
<tr>
<td><strong>Transition Zone</strong></td>
<td>Between primary zone and secondary zone</td>
<td>Rising interval</td>
</tr>
</tbody>
</table>

![Figure 15. Illustration of edge pillars and their categories](image)
Figure 16 shows clearly how receding pillars in each zone start the depinning-pinning transition in one period. If a pillar is marked with color, this means that the contact line has just depinned from the neighboring pillar on the left and started to pin on this pillar. Time interval between events has also been marked.

Figure 16. Receding contacted pillars evolution over time for experiment #4, time required for the transition is highlighted in the picture.
The pillars at the very end of the receding edge are considered to be in the Primary Zone. It is interesting to note that the DSS force would start to fall in one period immediately after these group pillars initiated the depinning-pinning transition. Receding pillars in the Primary Zone contribute to the highest possible pinning force. This is because the projection of the surface tension on the moving direction there would be maximized.

*Residuals*

As we zoomed in and took a closer look at the video, it is noticed that there are liquid depositions on pillars that has been swiped by droplet, as you can see within the pink circles in Figure 17. This is a strong evidence that there were micro-capillary bridges formation and rupture as the droplet jumps from one column of pillars to another.

*Figure 17 liquid residues on pillars behind the receding edge*
CHAPTER 5: STICK-SLIP PHENOMENON AND THE CONTACT LINE EVOLUTION

Considering the analysis and results from previous chapters, we hypothesized that the stick-slip behavior is linearly correlated with the displacement of receding contacted pillars. This hypothesis is supported by closely look at video and force data in experiment 4, as is the main issue in this chapter.

5.1 Image Processing

Image Processing

The first challenge is to process the images in the video to a degree that would be identifiable by the computer. ImageJ processing tools (Bandpass Filter, Unsharpen Mask, Threshold Adjustment, etc.) are employed to sharpen the pillar edge. Grigola developed an algorithm to identify contacted pillars from the video. For details, please refer to [18].

Identifying receding contacted pillars

In order to identify receding contacted pillars and calculate for their displacements, two orthogonal coordinate systems are employed here.

The first one is Pillar Coordinate System (X, Y), as shown in Figure 18, with pillar substrate itself as the reference. +X is the droplet’s moving direction, relatively pillars moves in the –X direction. +Y is perpendicular to +X pointing downwards. During Dynamic Steady State in exp.4, the number of rows of contacted pillars remains the same from Y=1 to Y=13 (Shown in Figure 18). X=0 is randomly assigned to one column of pillars.
The other one is Location Coordinate System \((x, y)\), also as shown in Figure 18, with the camera window as a reference. \(+x\) is the droplet’s moving direction, \(+y\) is perpendicular to \(+x\) pointing downwards.

For each pillar, it will have a pair of coordinates \((X, Y)\) in pillar coordinate system, which is fixed overtime; it will also have another pair of coordinates \((x, y)\) in location coordinate system, which are a function of time \(\tau\):

\[
\begin{align*}
    x(X, Y) &= x(X, Y, \tau), \\
    y(X, Y) &= y(X, Y, \tau), \quad \tau > 0
\end{align*}
\]

Equation 4

In exp.4, the rows of contacted pillars remain \(Y=1\sim13\) throughout the dynamic steady state. Therefore, we can label receding contacted pillars 1\sim13 according to their corresponding \(Y\) values.

Figure 18: Pillar Coordinate System & Location Coordinate System, image is from exp.4.
5.2 Displacement of Receding Pillars

Displacement of One Contacted Pillar at the Receding Edge

The displacement of one contacted pillar at the receding edge in row Y is marked as $D_Y$.

$D_Y$ is calculated in the following way:

$(X = n - 1, Y)$ is a contacted pillar at the receding edge at $\tau = t_1$. If at time $\tau = t_2$ the contact line detached and reattached to the pillar in the next column, $(X = n, Y)$, the displacement $D_Y$ is set to be zero. As pillar $(X = n, Y)$ pins the contact line while moving towards $-x$ direction, its displacement $D_Y$ increases. At time $t = t_2 + \Delta t$ if CL stayed pinned at the pillar $(X = n, Y)$,

$$D_Y = |x(X = n, Y, t) - x(X = n, Y, t_2)|.$$  \hspace{1cm} \text{Equation 5}

If at time $\tau = t_3$ contact line detached from pillar $(X = n, Y)$, and reattached to pillar $(X = n + 1, Y)$, the displacement of this contacted pillar is set to be zero again.

$$D_Y = \begin{cases} 0, & \text{if CL moves from } (X = n - 1, Y) \text{ to } (X = n, Y) \text{ at } \tau = t_2 \\ |x(X = n, Y, t) - x(X = n, Y, t_2)|, & \text{if CL pins at } (X = n, Y) \end{cases}$$

In this way, we can calculate the displacement of each contacted pillar at the receding edge at time $\tau$.

Displacement of Receding Pillars

Displacement of receding pillars is calculated as the sum of displacements of each receding contacted pillars:

$$D = \sum_{Y=1}^{Y=13} D_Y$$ \hspace{1cm} \text{Equation 6}
5.3 Comparison of Displacement of Receding Contacted Pillars and Force Data

To better illustrate the correlation of force and displacements calculated from 8.3, both the two data sets were normalized by their maximum value and plotted in Figure 19. Green curve represents normalized displacement-time, while red curve represents normalized force-time. For unknown reasons the force-time data presents a wavy pattern with a smaller frequency, which is very well captured by the displacement-time data.

![Figure 19, normalized displacement-time and force-time data, exp. 4](image)

5.4 Discussion and Future Work

The energy input into this system is passive, which means that it will be as needed. The energy can be transformed into four parts:

1. Interfacial interaction induced heat
2. Vibration induced heat
3. Elastic energy of droplet’s deformation
4. Micro-capillary bridge formation & rupture dissipation
As for the stick-slip behavior of fakir droplet’s moving on micropillar arrayed substrates, (4) is the dominant factor. To further understand the stick-slip behavior, additional quantitative investigations into micro-capillary bridges need to be performed. Below is a list of recommended next steps:

(1) Forming and breaking the micro-capillary bridge under different conditions by changing each of the variables below:

- Liquid surface energy
- Shape of micro pillar’s top surface
- Dragging direction with pillar substrate as a reference
- Micro-capillary bridge break-up speed

The observing target could be rupture length of the micro-capillary bridge, and volume of liquid residue on top of the pillar

(2) Develop a model base on the understanding of micro-capillary bridge formation and rupture

(3) Test the droplet moving on micro-pillar arrayed substrates with difference speeds, compare the force & video output, to testify the micro-capillary hypothesis and modify the model
REFERENCE


function [data_ifft,t_ifft]=Process(filename,startline)

%%%%%% Part I, load & plot the data %%%%%%%
read=importdata(filename,' ',startline);
data=read.data;

t=data(:,1);
Fs=1/(t(2)-t(1));
y=data(:,2);
if 0 %If you need test the asymmetric triangular signal
    a=0.341;
    y=2.377*sawtooth((t-a)/0.1671*2*pi,(0.756))+50;
end

figure()
plot(t,y)
title('Original Signal')
xlabel('Time (s)')
ylabel('Signal (uN)')

%%%%%% Part II cut & plot a portion of data for fft & ifft %%%%%%%

Please specify the start & end point of cutting below%%

prompt='what is the CuttingTime_Start?';
CuttingTime_Start=input(prompt);

prompt='what is the CuttingTime_End?';
CuttingTime_End=input(prompt);

y=y((CuttingTime_Start<t)&(t<CuttingTime_End));
t=t((CuttingTime_Start<t)&(t<CuttingTime_End));

%translation
y=y-mean(y);

figure()
plot(t,y)
title('Signal after cut')
xlabel('Time (s)')
ylabel('Signal (uN)')
% Part III Fast Fourier Transform

[Y,f]=Fourier(y,t,Fs);

% Part IV, Cut & Inverse Fourier Transform

% Please specify the start & end of cutting frequency below
prompt='what is the CuttingFreq_Start?';
CuttingFreq_Start=input(prompt);

prompt='what is the CuttingFreq_End?';
CuttingFreq_End=input(prompt);

[data_ifft,t_ifft]=InverseFourier(CuttingFreq_Start,
CuttingFreq_End,Y,t,Fs);
end

function [Y,f]=Fourier(y,t,Fs)

%FFT
L=length(t);
NFFT = 2^floor(log2(L)); % Next power of 2 from length of y
NFFT=2^nextpow2(L);
Y = fft(y,NFFT)/L;
f = Fs/2*linspace(0,1,NFFT/2+1);
sp=2*abs(Y(1:NFFT/2+1));

% Plot single-sided amplitude spectrum.
CuttingFreq=Fs/2;
fs=f(f<CuttingFreq);
sp=sp(f<CuttingFreq);
% SP=sp'.*(fs.*fs);
figure()
% stem(fs,SP);
figure()
stem(fs,sp);
title('Single-Sided Amplitude Spectrum of signal')
xlabel('Frequency (Hz)')
ylabel('|Y(f)|')
end

function [data_ifft,t_ifft]=InverseFourier(CuttingFreq_Start,
CuttingFreq_End,Y,t,Fs)

L=length(t);
NFFT=2^nextpow2(L);
f = Fs/2*linspace(0,1,NFFT/2+1);
%y_ifft=Y((CuttingFreq_Start<=fs)&(fs<=CuttingFreq_End));
Y_ifft=Y;
Y_ifft((f<CuttingFreq_Start)|(f>CuttingFreq_End))=0.02;

%data_ifft=ifft(y_ifft,y_ifft_size(:,1))*y_ifft_size(:,1);
data_ifft=ifft(Y_ifft,NFFT,'symmetric')*L;
t_ifft=0:(1/Fs):((L-1)/Fs);
figure();

t_ifft=t_ifft(250:L);
data_ifft=data_ifft(250:L);
plot(t_ifft,data_ifft);
title('plot after ifft');
xlabel('Time (s)')
ylabel('Signal (uN)')
end
APPENDIX B: MATLAB CODES FOR SLOPE ANALYSIS

```matlab
function [SortSlopes, SortAmplitudes, SortIntervals]=SlopeAnalysis(data_ifft, t_ifft, MainFreq)

y=data_ifft;
t=t_ifft;
Fs=1/(t(2)-t(1));
t=(1:length(y))/Fs;t=t';
period=Fs/MainFreq;

[maximum,minimum]=GetExtremes(y,period);

%For demonstration
if 1
    figure();
    hold on;
    plot(t,y);
    title('Filtered data with peak & valley identified');
    xlabel('Time');
    ylabel('Filtered Signal, uN');
    plot(t(maximum),y(maximum),'or');
    plot(t(minimum),y(minimum),'og');
end

Extreme_Pos=[maximum,minimum];
L=length(Extreme_Pos);

Extreme_Nature(1:length(maximum))=1;
Extreme_Nature(length(maximum)+1:L)=-1;

[Extreme_Pos,I]=sort(Extreme_Pos);
Extreme_Nature=Extreme_Nature(I);

Slopes=zeros(1,L-1);
Amplitudes=zeros(1,L-1);
Intervals=zeros(1,L-1);

for i=1:L-1
    seg=Extreme_Pos(i):Extreme_Pos(i+1);
    Slopes(i)=GetSlope(y(seg),t(seg));
    Amplitudes(i)=y(Extreme_Pos(i+1))-y(Extreme_Pos(i));
    Intervals(i)=t(Extreme_Pos(i+1))-t(Extreme_Pos(i));
end

prompt='if the first point is green then type in 1; otherwise type in 2';
ss=input(prompt);
I_Intervals=Intervals(ss:2:end);

SortSlopes=sort(Slopes);
```
SortAmplitudes=sort(Amplitudes);
SortIntervals=sort(I_Intervals);

figure();
plot(SortSlopes,'*r');
title('Sorted Slopes')
xlabel('Sequence #')
ylabel('Slope uN/s')

figure()
plot(SortAmplitudes,'*g');
title('Sorted Amplitudes')
xlabel('Sequence #')
ylabel('Amplitudes uN')

figure()
plot(SortIntervals,'*b');
title('Sorted Type I Intervals')
xlabel('Sequence #')
ylabel('Intervals s')
end

function [maximum,minimum] = GetExtremes(y,period)
% This function return the location of maximum and minimum from a
% oscillating function.
%
% It requires:
% 1, the amplitude must be generally consistent;
% 2, the approx period of the oscillation must be given.

%For debug use
if nargin==0
    load('d50r25_June2011.mat');
    cut=2000:6000;
    y=d50r25_0626_4(cut,2);
    period=100;
end

% 1, find the center line of y by doing a moving average with
% span=10*period.
yc=smooth(y,period*10);

% 2, find the localized amplitude by substracting yc from y.
yl=y-yc;

% 3, find a threshold value to isolate and locate the local extremes.
TV=mean(abs(yl));

% 4, find the region that contains the peaks and valleys
isPeak = yl>2*TV;
isValley = yl<-2*TV;
% 5, We want to combine continuous small peaks/valleys into a big one.

Altitude=isPeak-isValley;

FirstPV=find(Altitude,1); %A starting point. PV stands for peak or valley

PreviousPV_Position=FirstPV;
PreviousPV_Altitude=Altitude(FirstPV);
for pos=FirstPV+1:length(Altitude)
    if Altitude(pos)~=0 %Find something
        if PreviousPV_Altitude*Altitude(pos)>0
            %Count the plateaus between peaks as peaks. Same for valleys.
            Altitude(PreviousPV_Position:pos)=PreviousPV_Altitude;
        end
        PreviousPV_Position=pos;
        PreviousPV_Altitude=Altitude(pos);
    end
end
isPeak = Altitude>0;
isValley = Altitude<0;

% 5x, Debug use only
if 0
    clf
    hold on
    plot(y)
    x=1:6001;
    plot(x(isValley),y(isValley),'r-');
    plot(x(isPeak),y(isPeak), 'g-');
end

% 6, Identify the segmented region
SegmentPeak=IdentifySegments(isPeak);
SegmentValley=IdentifySegments(isValley);

% 7, Find the local extreme in each segment.
maximum=SegmentedMaximum(y,SegmentPeak);
minimum=SegmentedMaximum(-y,SegmentValley);
end

function Segments=IdentifySegments(b)
% b consist of a sequence of 1 and 0, something like this
% 11111111111110000000000011111111
% This function return the start and end of each continued 1 segment.
if size(b,1)~=1
    b=b';
end

if size(b,1)~=1
    error('I need a vector');
end

% (Assuming b starts and ends with 0)

b_change=diff(b);
Starts=find(b_change==1)+1;
Ends=find(b_change==-1);

% Now correct the assumption.
if b(1)==1
    Starts=[1 Starts];
end

s=length(b);
if b(s)==1
    Ends=[Ends s];
end

Segments=[Starts;Ends;];
end

function MaximumPosition=SegmentedMaximum(y,Segment)
    Number_of_Segments=size(Segment, 2);
    MaximumPosition=zeros(1,Number_of_Segments);
    %MaximumValue=zeros(1,Number_of_Segments);
    for i=1:size(Segment, 2)
        y_local=y(Segment(1,i):Segment(2,i));
        [C,I]=max(y_local);
        % MaximumValue(i)=C;
        MaximumPosition(i)=I+Segment(1,i)-1;
    end
end

function k = GetSlope(y,x)
if nargin<2
    if size(y,1)==1
        x=1:size(y,2);
    elseif size(y,2)==1
        x=1:size(y,1);
        x=x';
end
else
    error('Input not a vector')
end

p=polyfit(x,y,1);

k=p(1);

end