Vi-Liquid: Unknown Liquid Identification with Your Smartphone Vibration

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Motivation

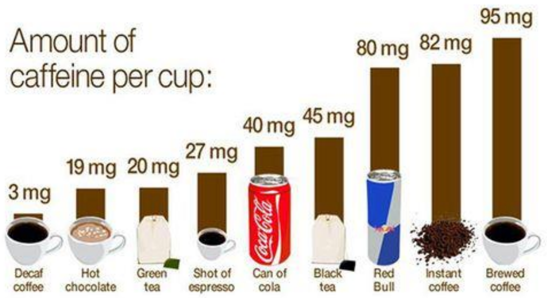
1. The potential application scenarios of ubiquitous liquid testing.

Public transportation

Fake luxury perfume

In-home urine testing

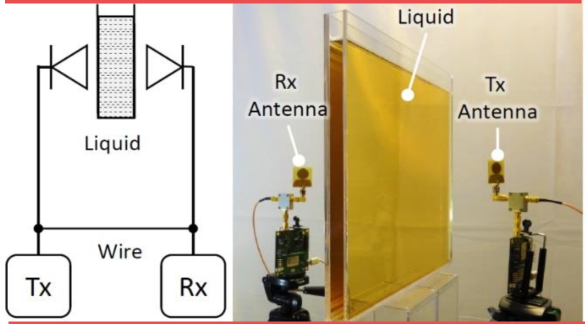
monitoring Caffeine intake from drinks



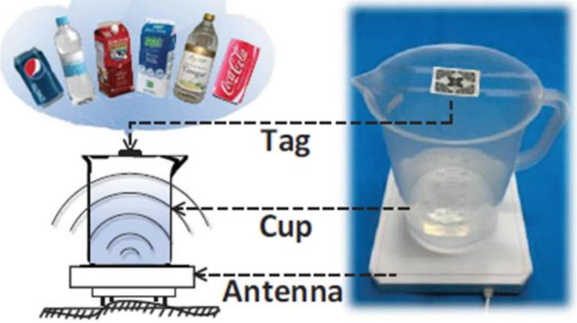
2. The existing liquid testing systems require specialized external devices

Commercial hazardous liquid detector

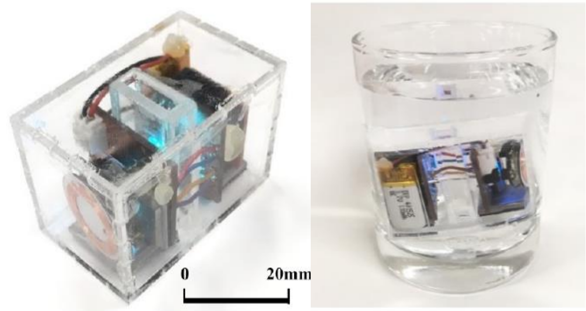
UWB devices: LiquID [*MobiSys '18*]



RFID devices: TagScan [*Mobicom '17*]



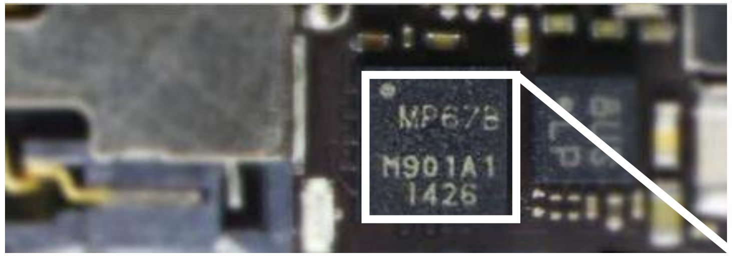
LED devices: AI-light [*Ubicomp '18*]



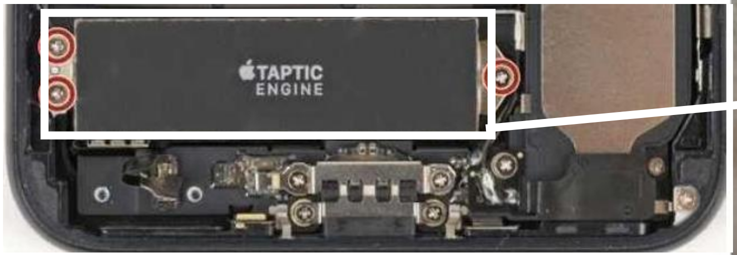
3. Whether we can identify unknown liquids with a commercial device, such as a smartphone ?

Vi-Liquid

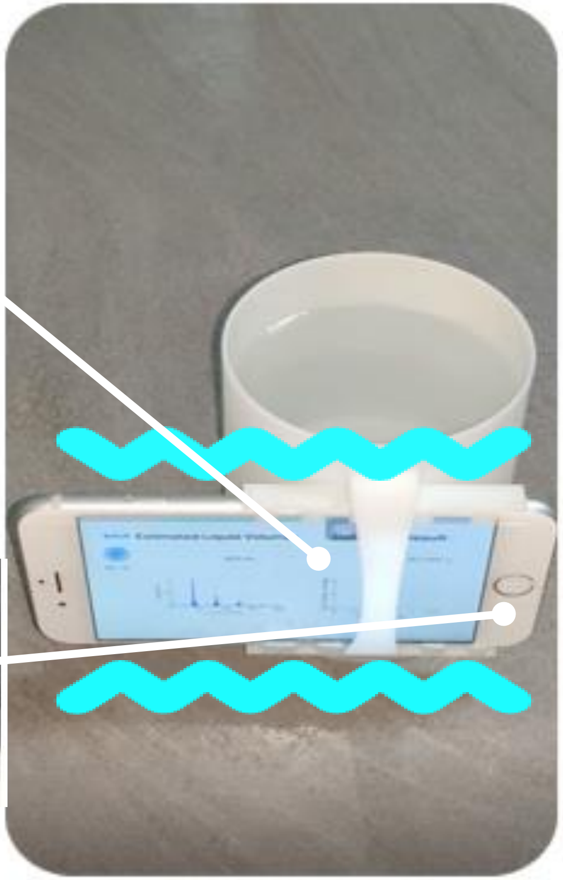
Proposed: **Liquid Viscosity** Measurement on **Smartphones** using **Vibration**



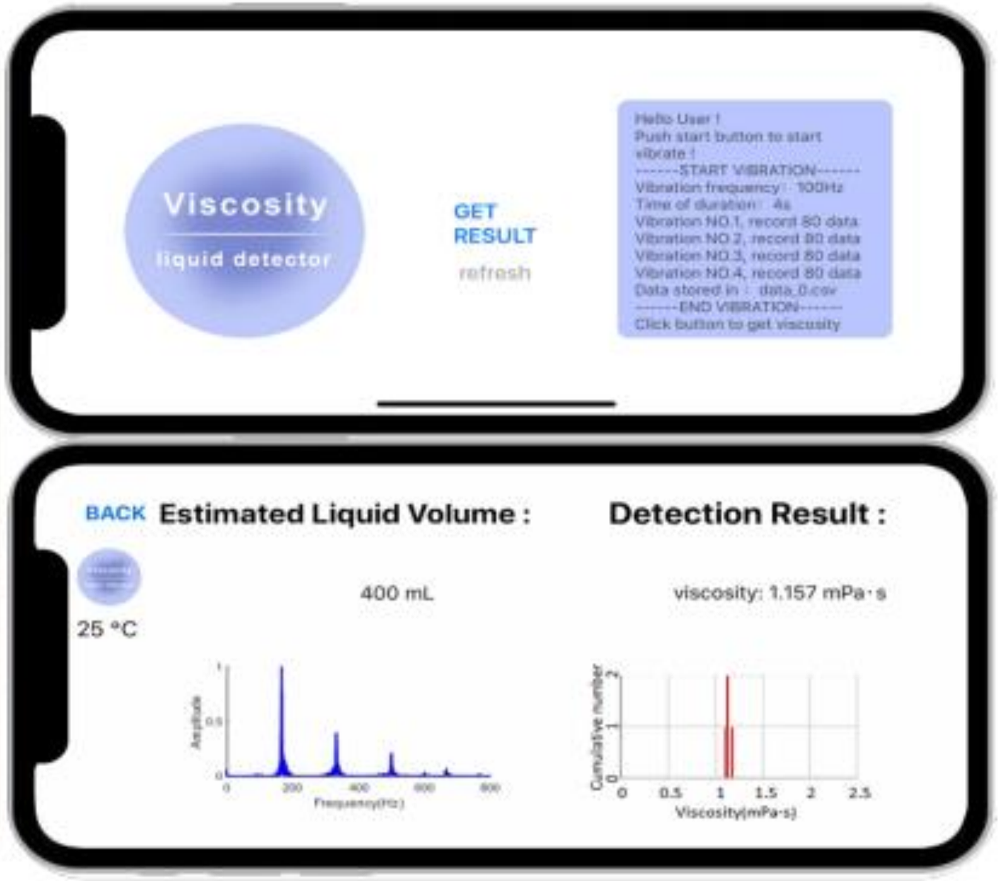
Built-in accelerometer



Built-in vibro-motor



Using iphone to Measure
Liquid Viscosity



The user interface

Challenges

(i) It is unclear how to calculate the viscosity by leveraging the influence and physical characters from active vibration to the liquid. It is necessary to build up a model.

Liquid viscosity ←? Relationship ?→ **Vibration signals**

(ii) The maximum sampling rate through API is limited to 100Hz in the COTS smartphones, the sampled signals are distorted and causing measurement errors.

Accelerometer sampling rate —Limited→ **100Hz**

(iii) The change of liquid volume makes the viscosity measurement inconsistent. The vibration signal directly transmitted to the accelerometer overwhelms the low SNR signal reflected by the target liquid.

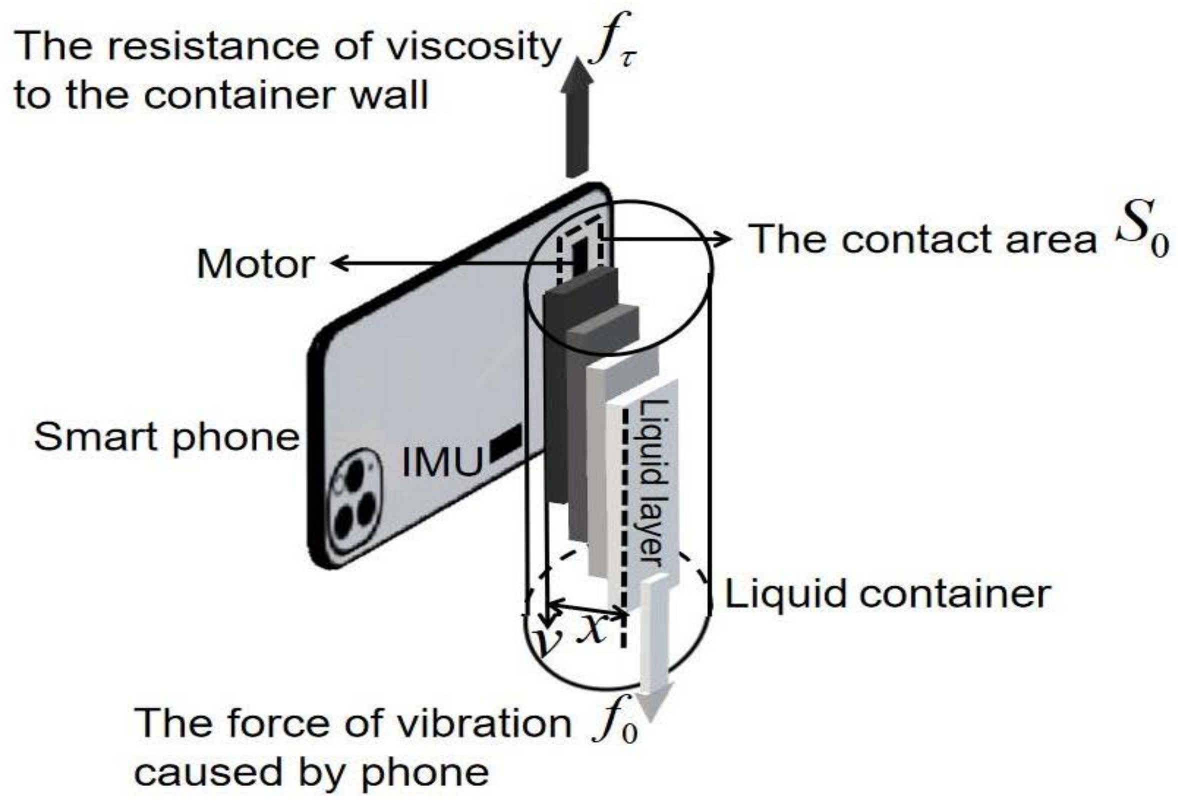
Two main interferences:

① **Direct transmission vibration**

② **Liquid volume**

Theoretical Models

1. Liquid Viscosity and the Shearing Force



Liquid Viscosity $$\eta = \frac{hN}{V} e^{-\frac{\Delta G}{RT}} \quad (1)$$

ΔG: Gibbs energy change of the molecule
V: Molar volume of the molecule
T: Temperature
h : Prang Gram **constant**
N : Avogadro **constant**
R : Boltzmann **constant**

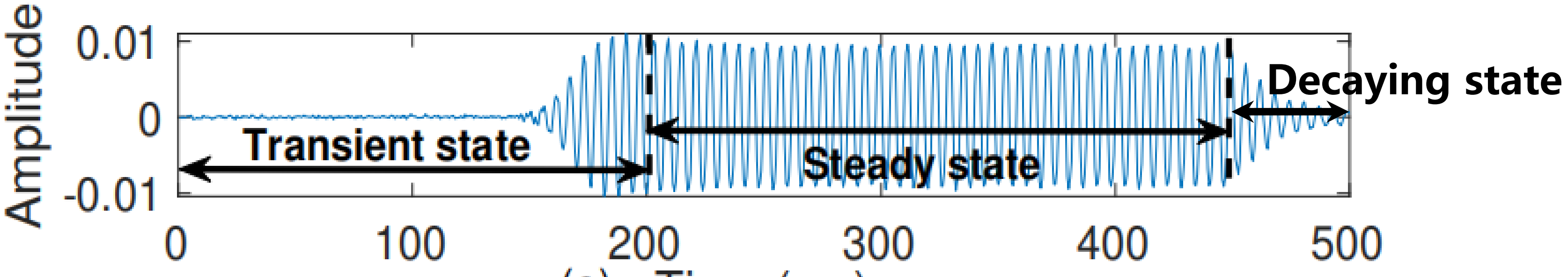
Shearing Force $$f_\tau = \eta S_0 \frac{v}{x} \quad (2)$$

η: Viscosity
S_0: Contact area between the liquid layer and container
v: Movement speed of the liquid
x: Layer depth of moving liquid

Given a certain liquid volume and vibration,
$S_0 \frac{v}{x}$ can be considered as **constants**

Theoretical models

2. Viscosity Calculation leveraging Vibration



(a)

Steady state

$$m\frac{d^2x}{dt^2}+\beta\frac{dx}{dt}+kx=(f_0-f_\tau)\,sin(\omega t) \qquad (3)$$

$$x_{vib}=\frac{f_0-f_\tau}{\sqrt{k-\omega^2m)^2+(\beta\omega)^2}}sin(\omega t-\phi) \qquad (4)$$

$$A=\frac{f_0-f_\tau}{\sqrt{(k-\omega^2m)^2+(\beta\omega)^2}} \qquad (5)$$

Decaying state

$$m\frac{d^2x}{dt^2}+\beta\frac{dx}{dt}+kx=0 \qquad (6)$$

$$x_{decay}=Ae^{-\frac{\beta}{2m}t}\sin(\sqrt{\frac{k}{m}}\sqrt{1-\left(\frac{\beta}{2\sqrt{km}}\right)^2}\,t+\theta) \qquad (7)$$

$$\Lambda=\frac{x_{decay}(t)}{x_{decay}(t+T)}=e^{T\frac{\beta}{2m}} \qquad (8)$$

β: Damping coefficient affected by viscosity

f_τ: Shearing Force

f_0: External force constant

k: Container elastic coefficient constant

ω: Angular frequency of vibro-motor

m: Mass of the vibrated liquid layer (known as Stokes boundary layer)

Feasibility Study

Experimental Setup

Fig. 1

1. The Viscosity Uniqueness of Liquids

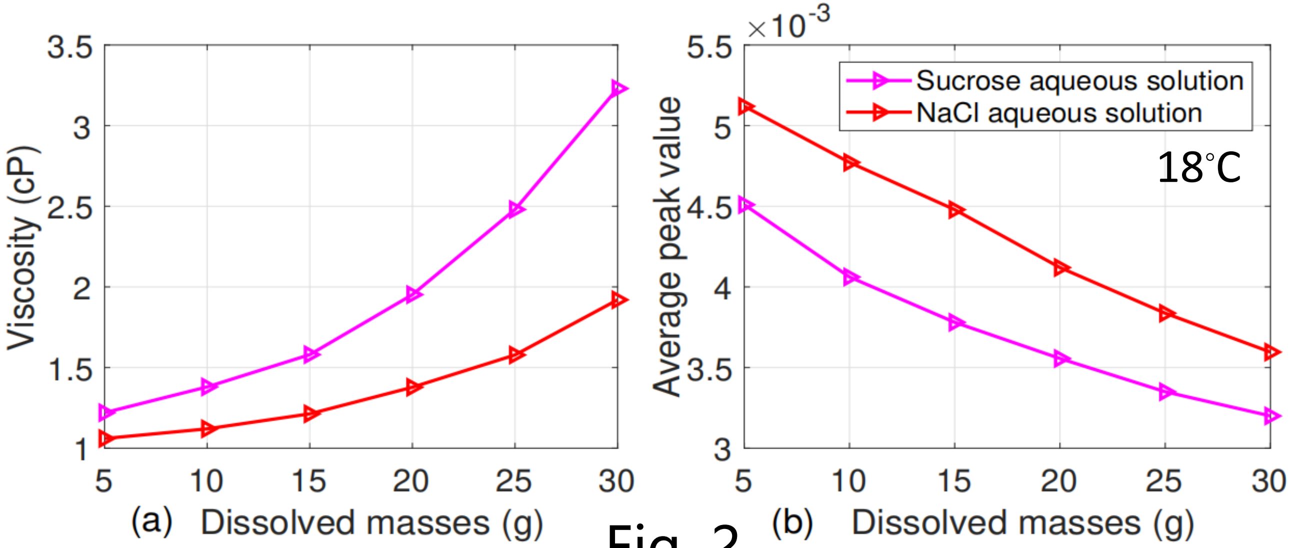


Fig. 2

2. The Impact of Mass

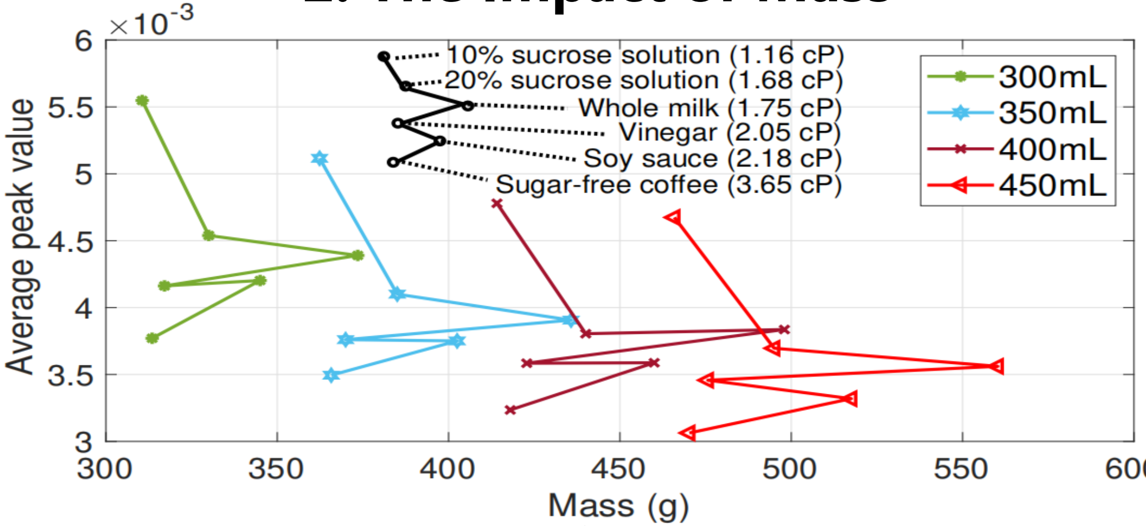


Fig. 3

3. Attenuation in decaying-state

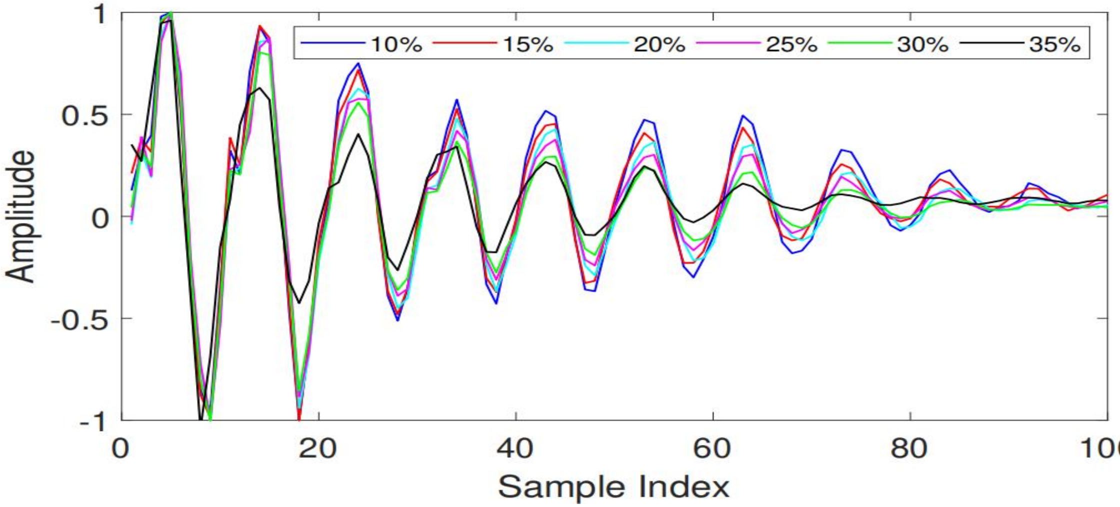
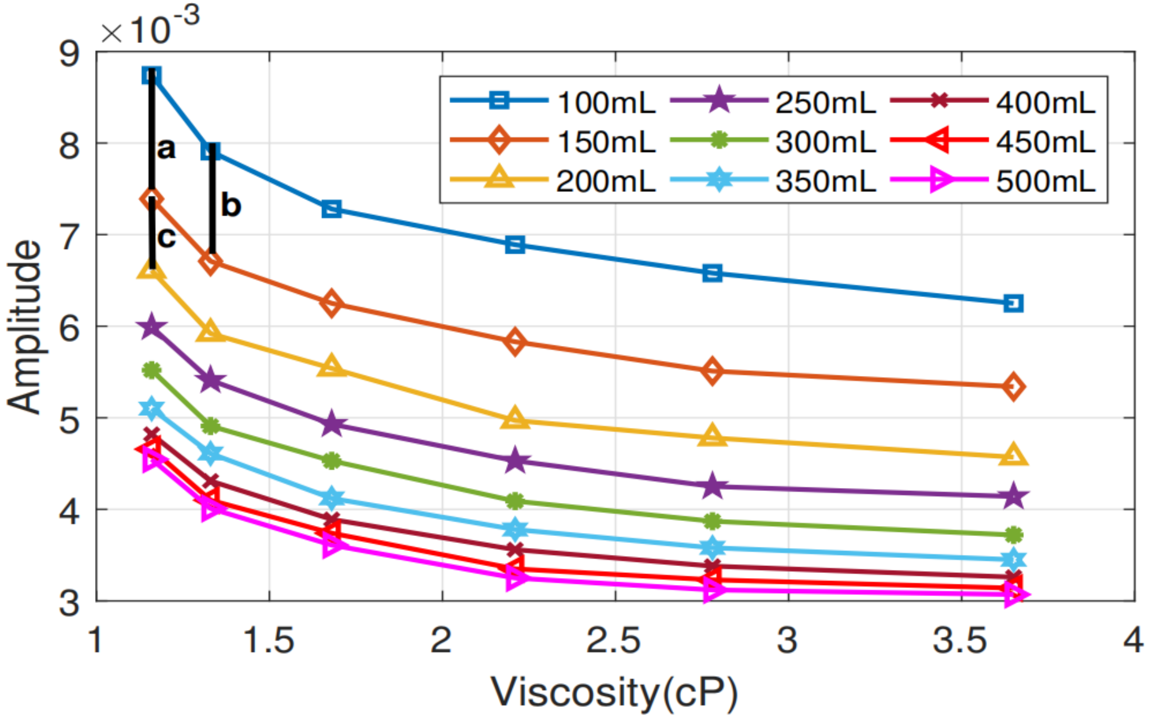


Fig. 4

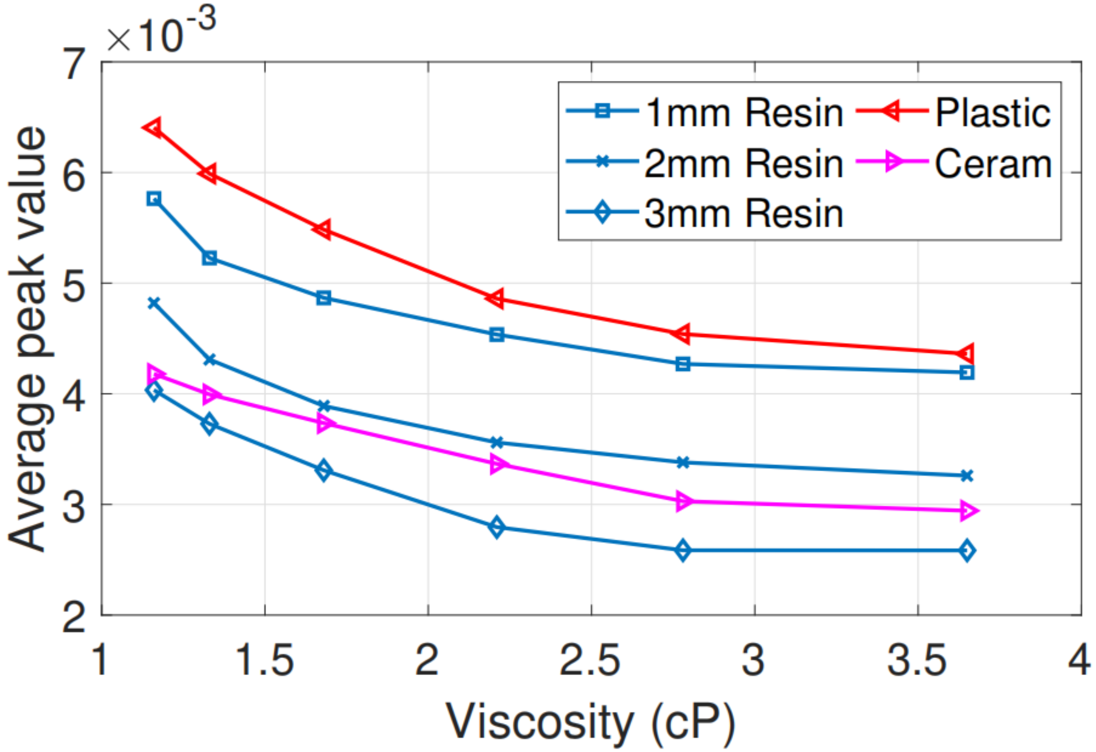
Feasibility Study

4. The Volume interference



Affect contact area between the liquid layer and container S_0.

5. The Impact of Container



Affect container elastic coefficient constant k.

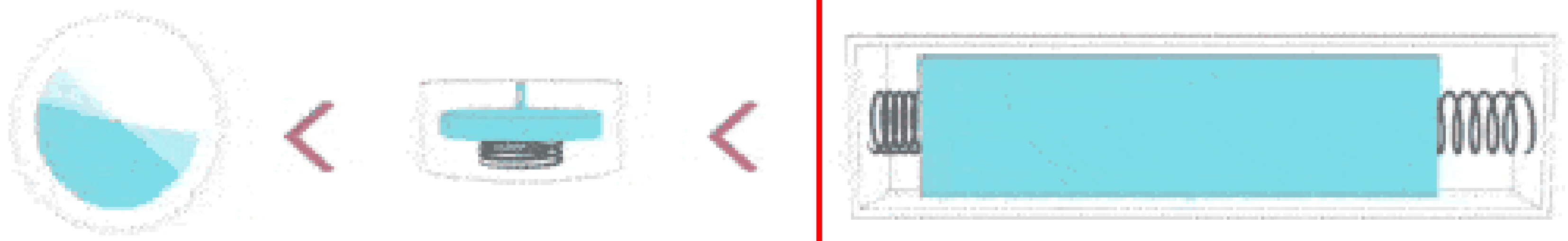
System Design

1.Vibro-motor Selection

Eccentric rotor motor

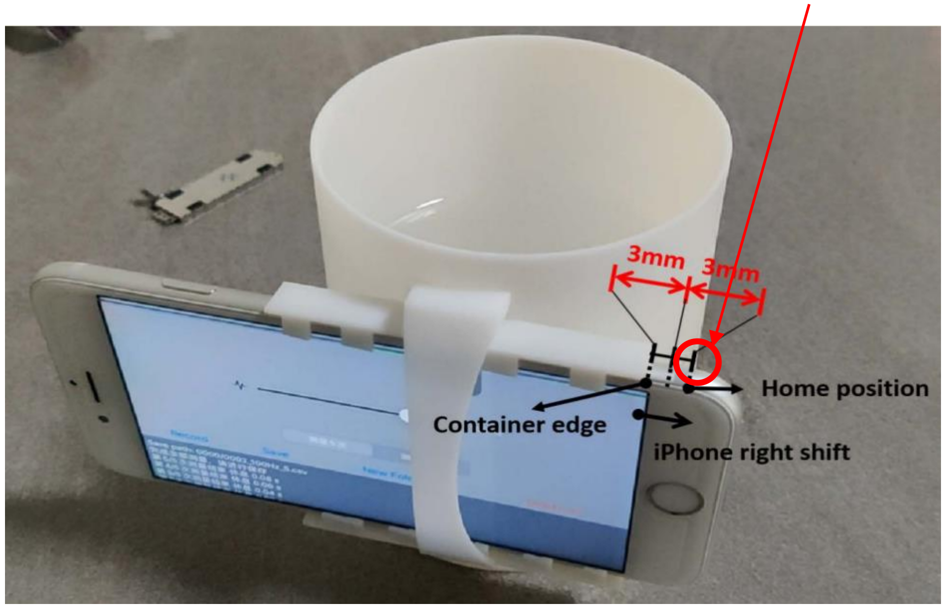
Z axis linear motor

X axis linear motor

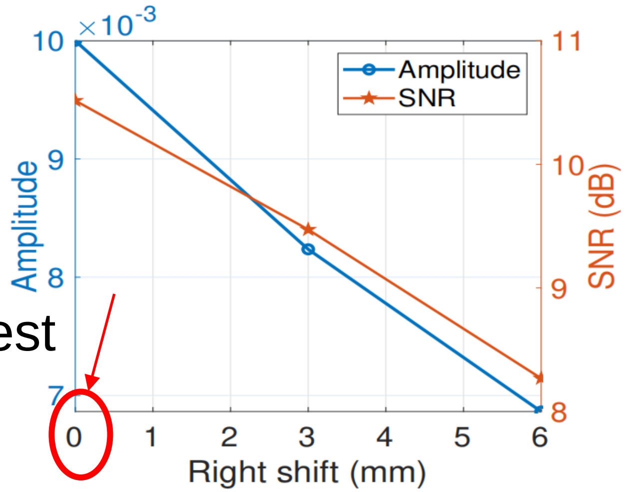


System Design

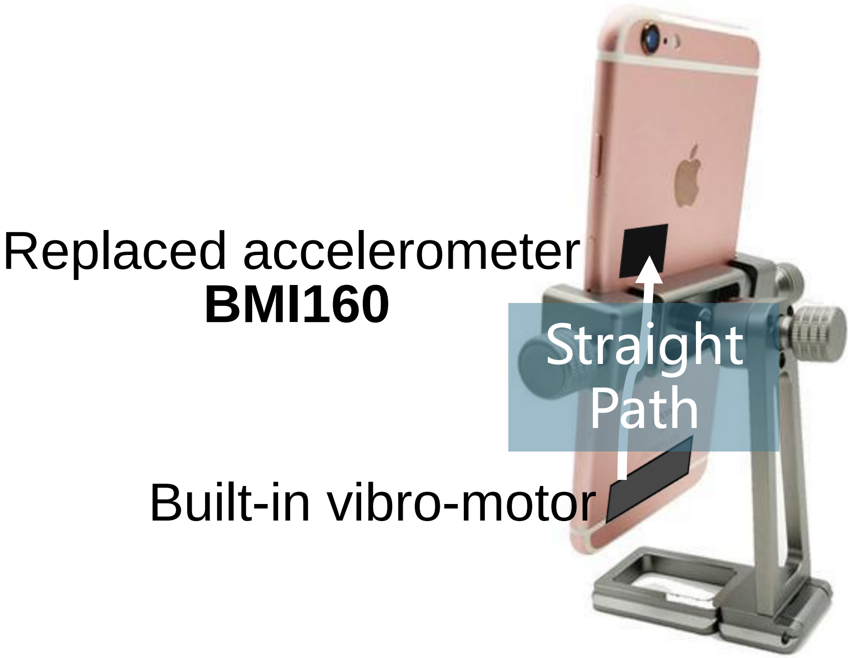
2. Mobile Phone Placement Selection



Select the highest SNR position



3. Combating Straight Path Interference



Original Signal

$$X_{NS} = X - S$$

None Straight path Amplitude-frequency Signal

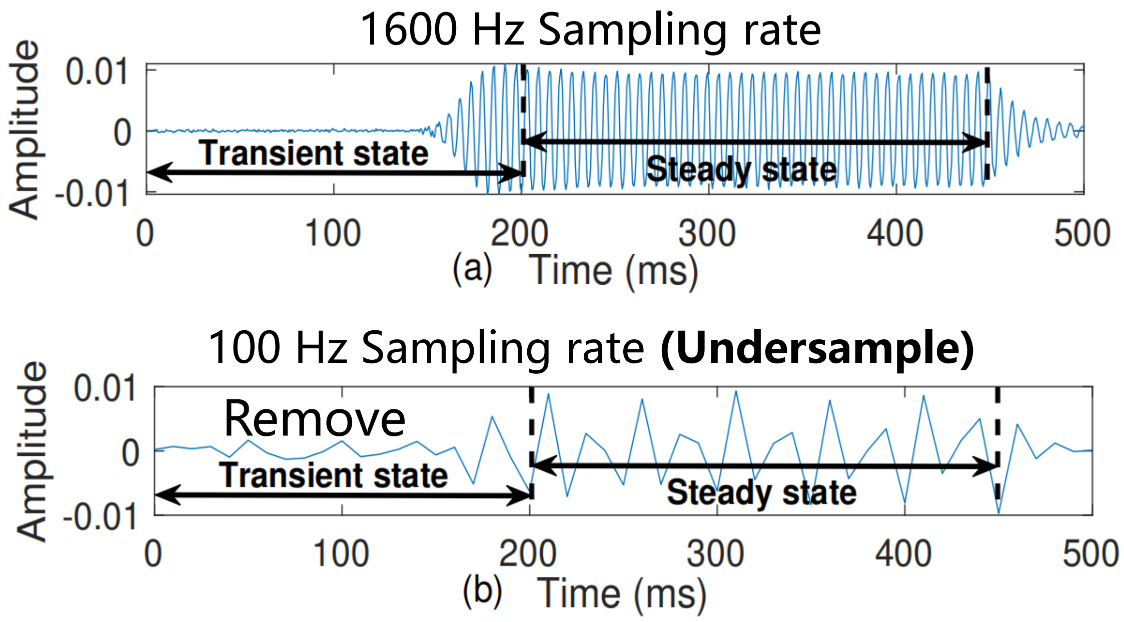
Straight Path

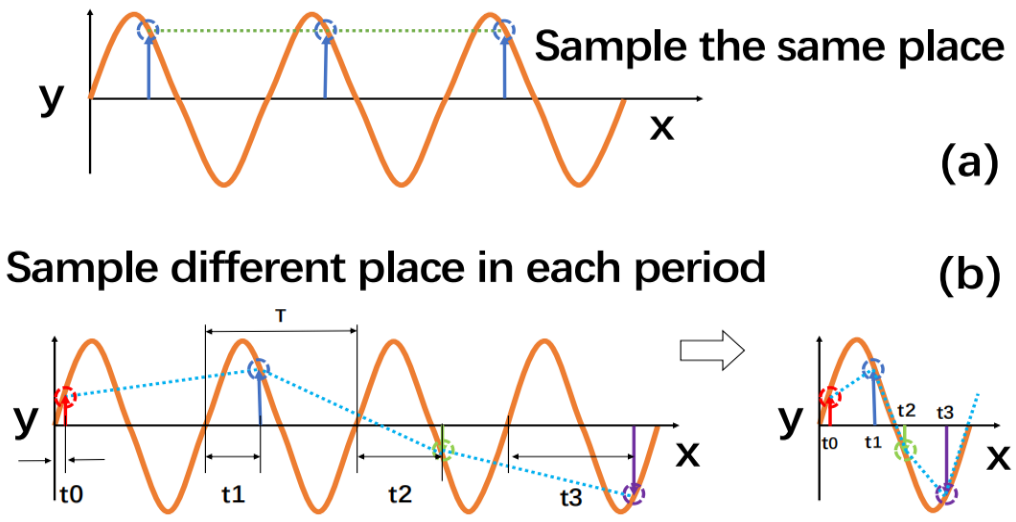
System Design

4. Supersampling Rate Reconstruction (SRR) (Sampling rate: **100 Hz** ⟶ **400 Hz**)

Challenge:
The vibration frequency of vibro-motor at around **167 Hz**

Solution:
Sample at a distinct time point in each period (e.g., start sampling after $t0$, $t1$, $t2$, and $t3$)





System Design

5. Orthogonal Matching Pursuit based Reconstruction (OMPR)

(Sampling rate: **400 Hz** → **1600 Hz**)

Solution:

The low sampling signal can express as

$$y = \varphi x$$

x: the high sampling rate signal

φ: sampling matrix

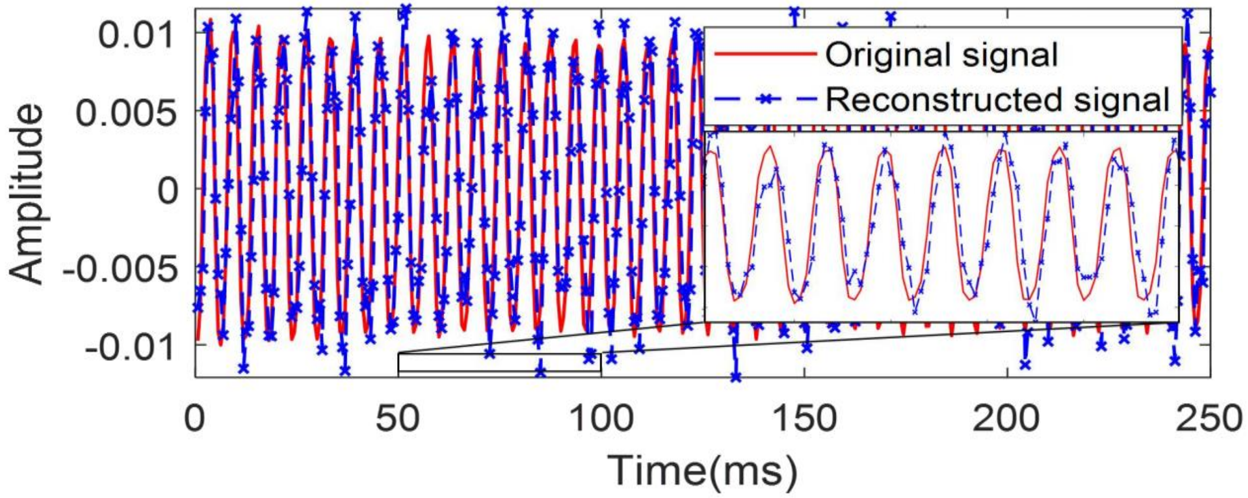
We know that the original high sampling rate signal has sparsity in the discrete Fourier transform domain, and the sparsified signal can be expressed as f:

$$y = \varphi \phi f$$

ϕ: an inverse transform operator

$\varphi\phi$: the observation matrix T.

Result:



System Design

5. Combating Volume Change Impact

Helmholtz vibration theory

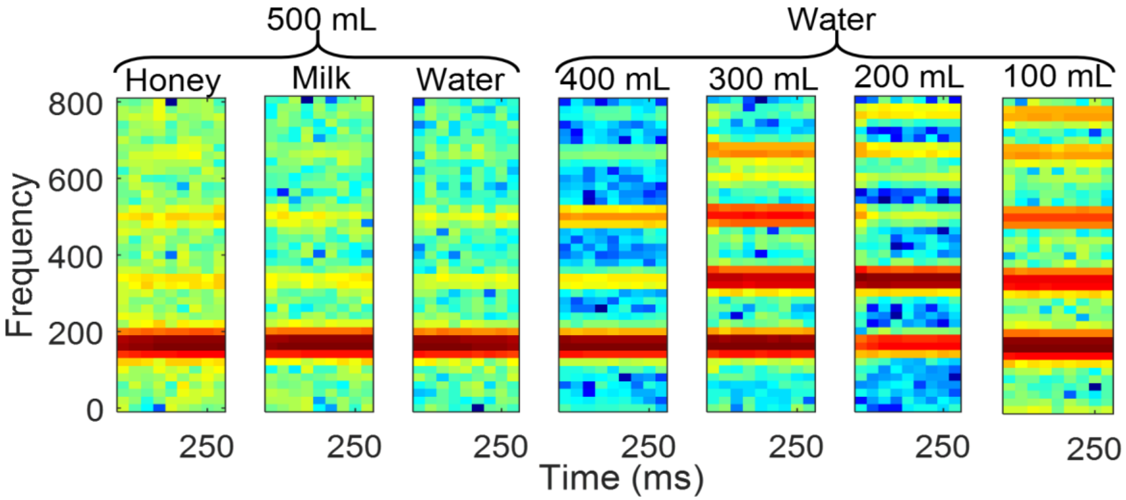
propagation speed of vibration

Resonance frequency

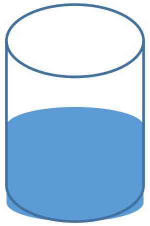
$$f_r = \frac{v}{2\pi}\sqrt{\frac{C}{V_l}}$$

Container conductivity

liquid volume



The volume weight vector W_{volume}

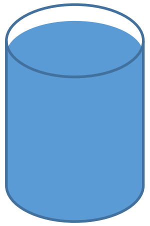


certain volume liquid

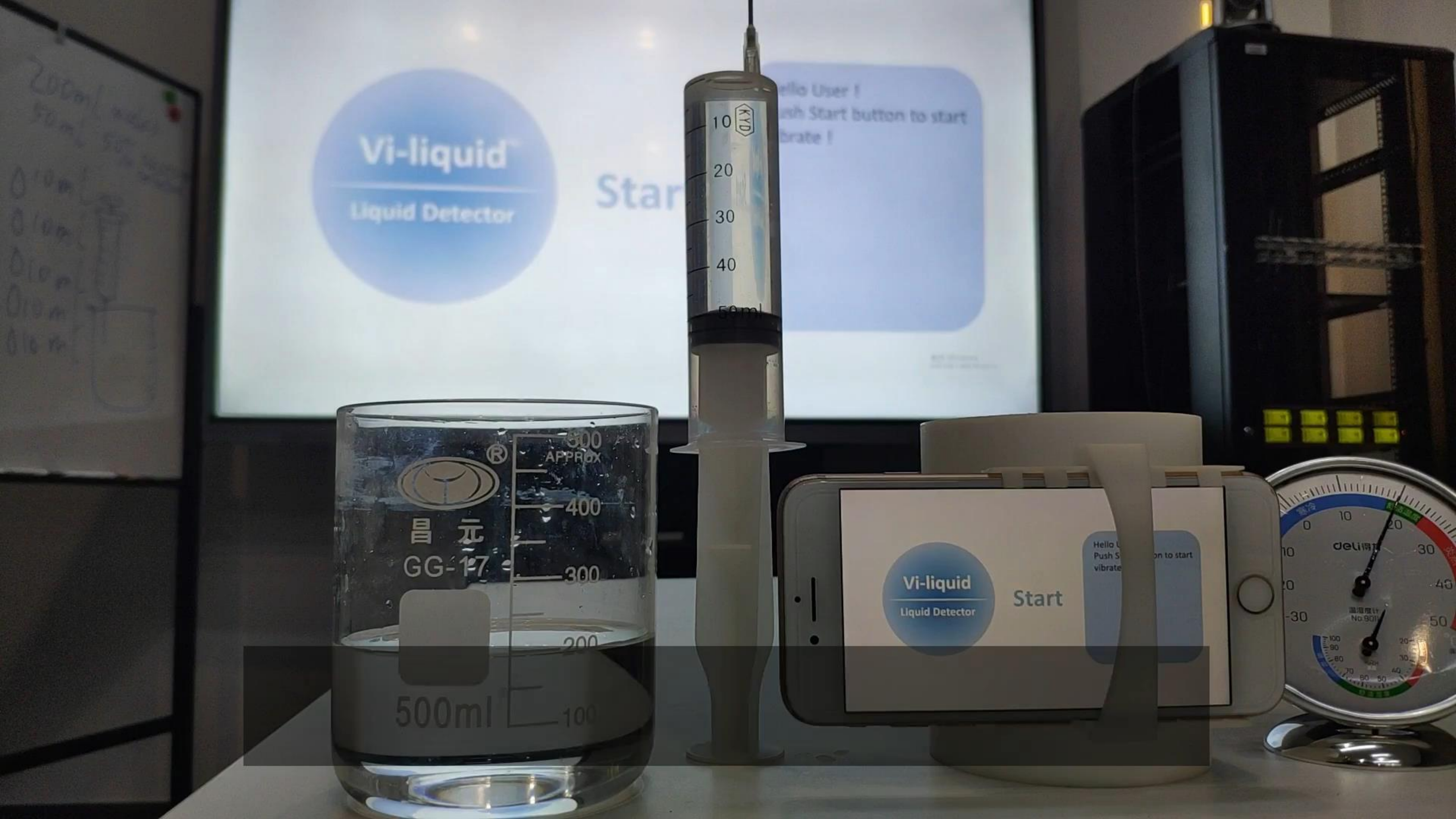
the amplitude of certain volume liquids at frequency bin i

$$W_{volume} = \left[\frac{a^{vol_1}}{a^{ref_1}}, \dots, \frac{a^{vol_i}}{a^{ref_i}}, \dots, \frac{a^{vol_{800Hz}}}{a^{ref_{800Hz}}}\right]$$

the amplitude of reference liquid at frequency bin i



500 ml liquid as the reference liquid

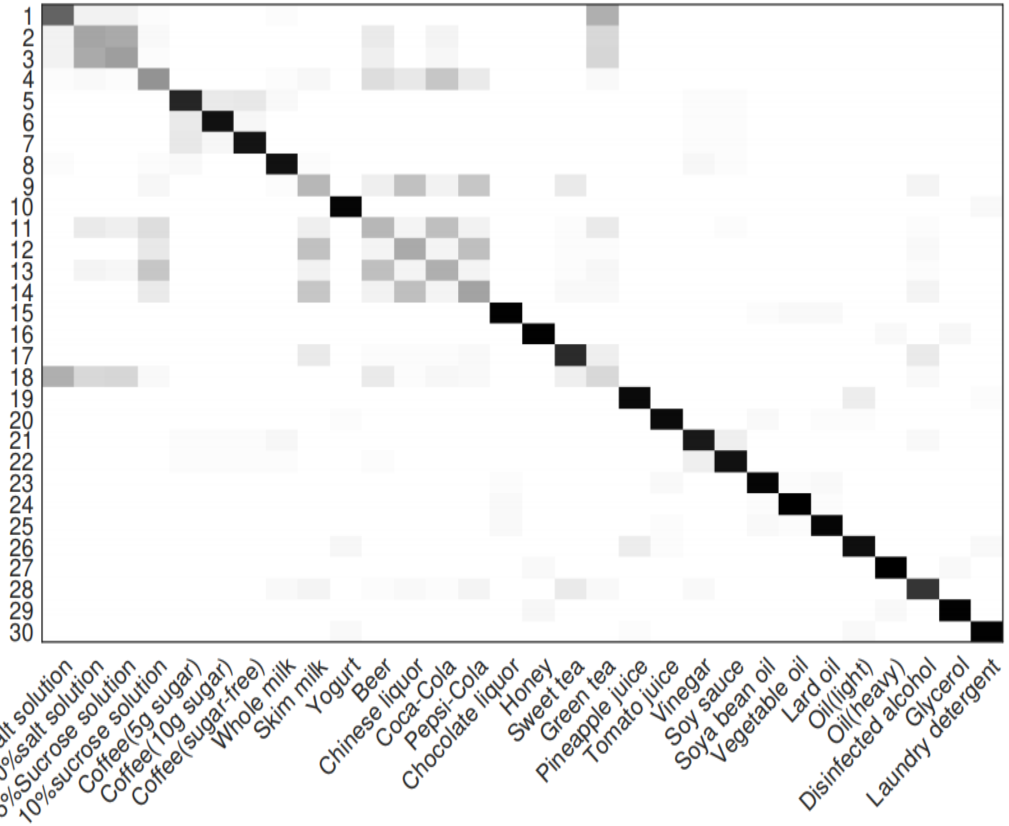

Vi-liquid
Liquid Detector
Start
ello User !
ush Start button to start
ibrate !
KYD
10
20
30
40
50ml
昌 元
GG-17
500ml
APPROX
400
300
200
Vi-liquid
Liquid Detector
Start
deli

Evaluation

1. Liquid Identification Performance

Average classification accuracy is **95.47%** for 30 kinds of liquids. KNN (K=1)

- iPhone 7P & 3D-printed container
- 10 times measurement
- 30 different liquids



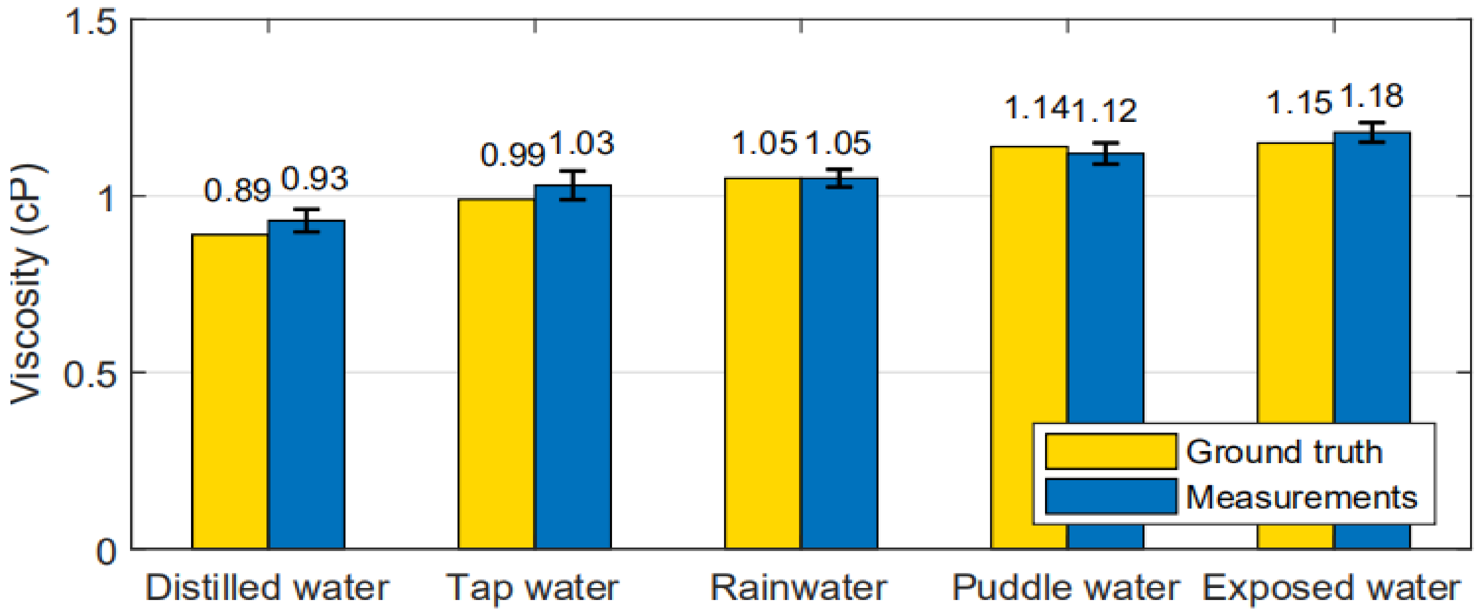
Comparing to the ground truth, the mean relative error of our system is **2.9%**

Liquid	β	$f_{\tau(N)}$	Vi-Liquid(cP)	GT(cP)	Error(%)
5%salt solution	0.8775	0.0134	1.03±0.019	1.00	3.00
10%salt solution	0.8757	0.0142	1.09±0.019	1.07	1.87
5%sucrose solution	0.8760	0.0140	1.08±0.025	1.06	1.89
10%sucrose solution	0.8745	0.0155	1.19±0.031	1.16	2.59
Coffee(10g sugar)	1.3770	0.0498	3.83±0.194	3.78	1.32
Coffee(15g sugar)	1.4392	0.0525	4.04±0.094	3.94	2.53
Coffee(sugar-free)	1.3566	0.0489	3.76±0.169	3.65	3.01
Whole milk	0.8980	0.0218	1.68±0.119	1.75	4.00
Skim milk	0.8745	0.0156	1.20±0.075	1.26	4.76
Yogurt	55.545	2.0887	159.14±4.800	152.45	4.39
Beer	0.8748	0.0148	1.14±0.013	1.11	2.70
Chinese liquor	0.8745	0.0155	1.19±0.031	1.23	3.25
Coca-Cola	0.8747	0.0149	1.15±0.019	1.13	1.77
Pepsi-Cola	0.8745	0.159	1.22±0.013	1.24	1.61
Chocolate liquor	14.888	0.5625	43.28±0.756	40.06	3.22
Honey	1009.8	37.899	2815.28±58.88	3000.12	6.16
Sweet tea	0.8751	0.0166	1.28±0.025	1.32	3.03
Green tea	0.8782	0.0131	1.01±0.019	1.03	1.94
Pineapple juice	33.245	1.2518	96.29±3.78	100.02	3.72
Tomato juice	28.015	1.0555	81.19±1.45	79.03	2.73
Vinegar	0.9393	0.0261	2.01±0.056	2.05	1.95
Soy sauce	0.9799	0.0292	2.25±0.113	2.18	3.37
Soya bean oil	21.145	0.7976	61.35±0.756	59.29	3.47
Vegetable oil	10.214	0.3870	29.77±0.644	30.94	3.78
Lard oil	19.233	0.7258	55.83±0.756	53.18	4.98
Oil(light)	39.047	1.4695	113.04±1.906	108.49	4.19
Oil(heavy)	231.24	8.6821	684.31±3.325	658.12	3.98
Disinfected alcohol	0.8809	0.0189	1.45±0.075	1.42	2.11
Glycerol	273.09	10.253	788.67±4.800	800.45	1.47
Laundry detergent	70.319	2.6432	203.32±2.331	201.05	1.13

Evaluation

2. Water Contamination Detection

The average relative error is **2.56%**

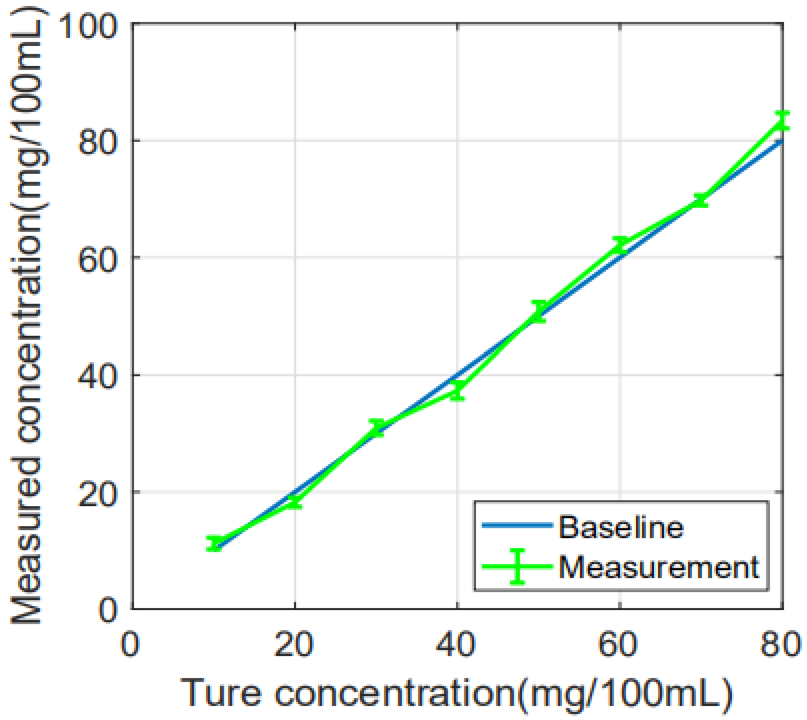


Evaluation

3. Concentration level estimation based on viscosity

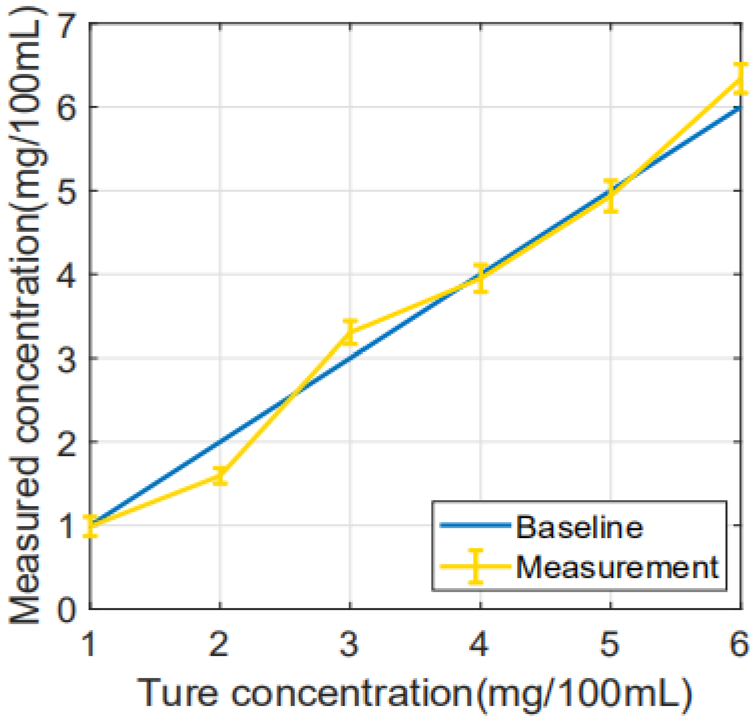
Sodium urate

Error of **1.15mg/100mL**



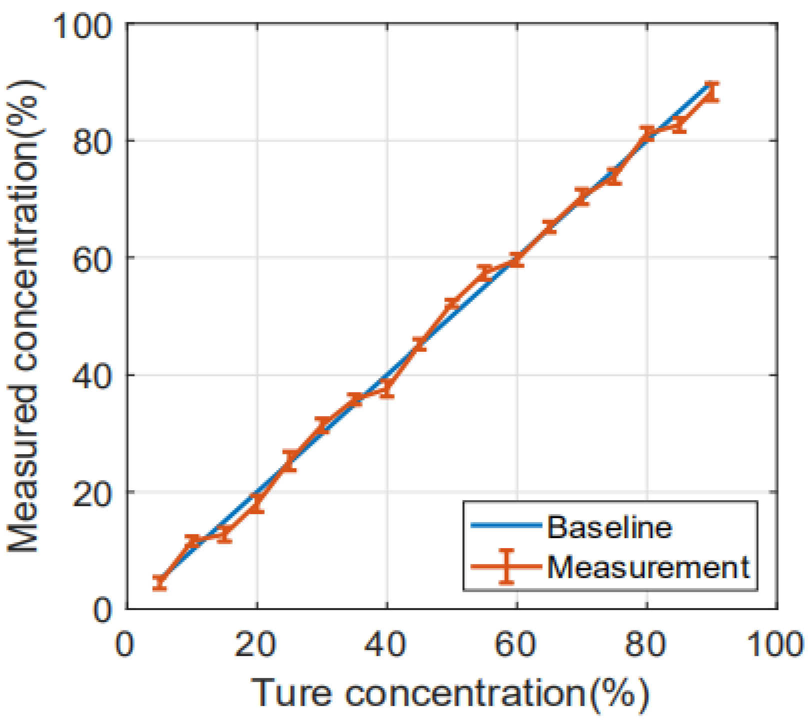
Ovalbumin

Error of **0.20mg/100mL**



Alcohol

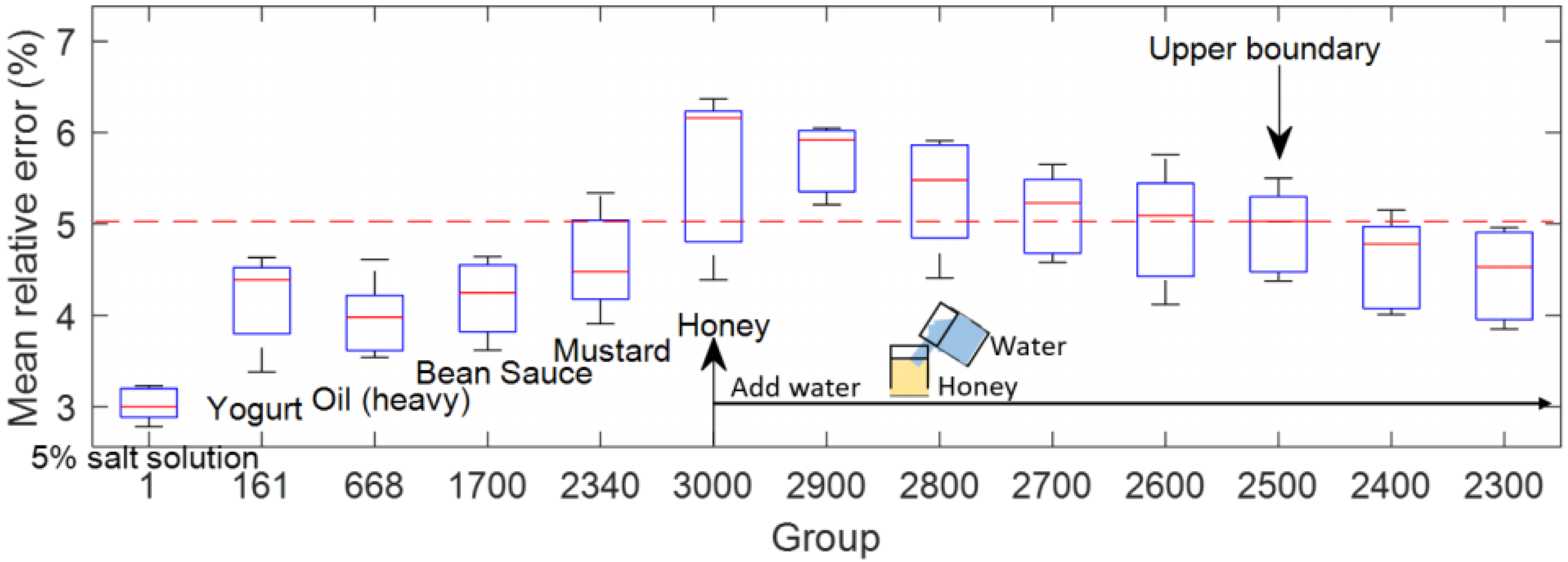
Error of **1.38 mass%**



Evaluation

4. The Boundary of Measurement

Regard that **2500 cP** as the upper boundary



Summary

- Vi-Liquid can accurately measure the liquid viscosity using vibration signals on smartphones
- We establish a novel calculation model that links vibration with viscosity and validate the feasibility on a smartphone
- We found the proper *SRR* and employ *OMP reconstruction* to restore the undersampled signal
- We cancel the straight path interference and volume change impact to improve the system performance

Thank you for your listening!