Noncontact Determination of Fluid Properties by Means of Focused Acoustics

Senior Honors Thesis Presentation

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Outline I

1. Introduction
    - Introduction
    - History and Other Methods
2. Experiment and Setup
    - Overview
    - Procedure
    - What's going on
3. Theory
    - Overview
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    - Fluid Dynamics
4. Results
    - Preliminary Analyses

Outline II

- Results

5. Future Work
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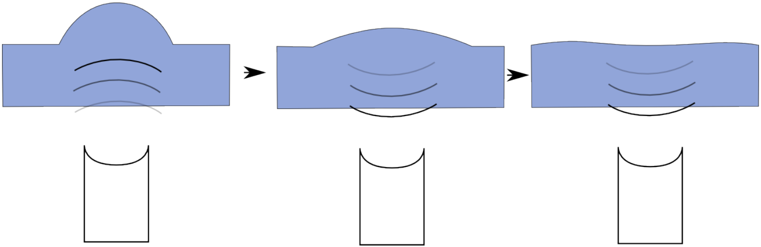
   - Curiosities

6. Acknowledgments

Basic Overview

An ultrasonic transducer is used to create a small mound on the surface of a liquid. The same transducer is then used to measure the height of the mound as it rises and falls. By looking at the time it takes the mound to rise and fall, and the maximum height, we can tell something about the surface tension and viscosity.



Impetus

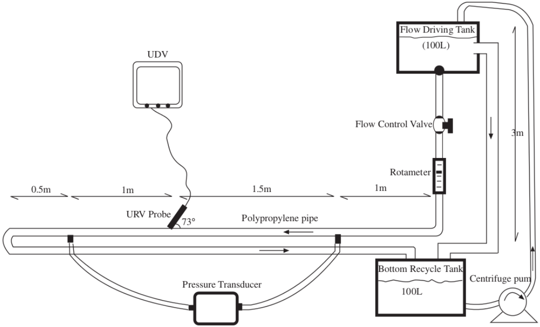
- Playing with Acoustic Drop Ejection
- Wondered if there was a way to detect surface tension and viscosity
- Noticed that mound forms when out of focus or not enough energy to eject

Applications

- Physics — Determine fluid properties even with small or volatile fluids
- Chemistry — Monitor chemical reactions by determining viscosity or surface tensions
- Biology — Monitor biological reactions without contaminating samples

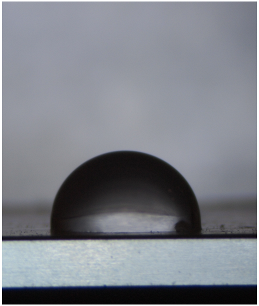
Viscometry

Capillary Viscometer[11]

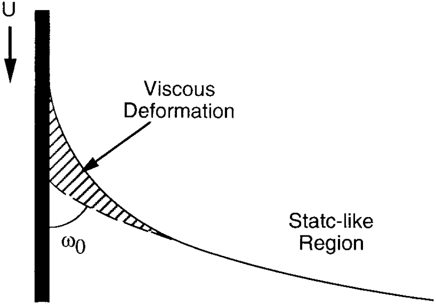


Ultrasonic Doppler Viscometer[5]

Surface Tension Techniques



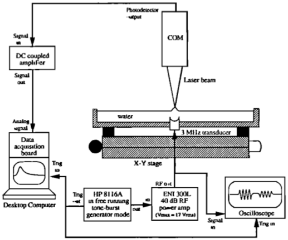
Contact Angle Surface Tension Measurement[10]



Wilhelmy Plate Method[8]

Laser Imaging of Mound Relaxation

- Method devoloped at Stanford University[1]
- Uses focused acoustics to form mound
- Uses laser to measure height of mound as it relaxes

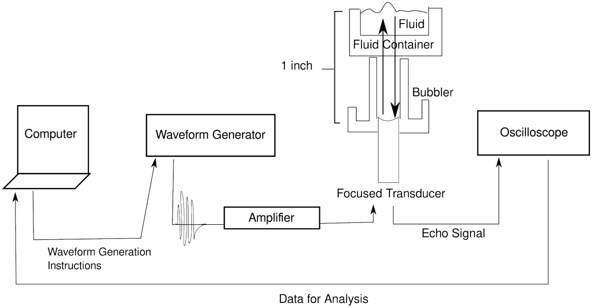


Novelty & Advantages

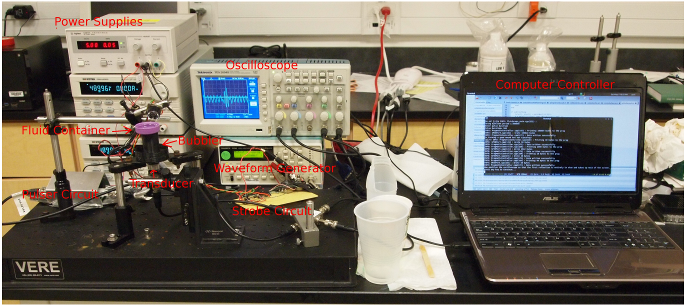
- Use same transducer for both mound formation and height measurements
- No lasers, needles, etc.
- For certain container materials, fluid does not need to be removed from container
- Very small amounts of fluid and containers can be used

Experiment and Setup

Schematic


Fluid
Fluid Container
1 inch
Bubbler
Computer
Waveform Generator
Oscilloscope
Focused Transducer
Amplifier
Echo Signal
Waveform Generation
Instructions
Data for Analysis

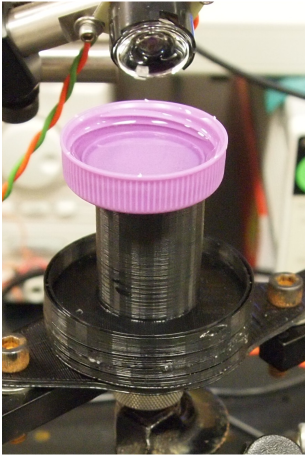
Actual Setup



Procedure

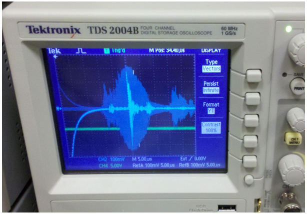
Prepare the Sample

1. Clean out bottle cap
2. Fill with 5 mL of solution (Concentrations vary from 0% to 100%)
3. Fill bubbler to top
4. Place bottle cap on bubbler



Focus the transducer

1. Lower transducer
2. Fill bubbler with water
3. Place cap on bubbler
4. Repeatedly Send echo signal
5. Raise transducer until echo return signal reaches maximum



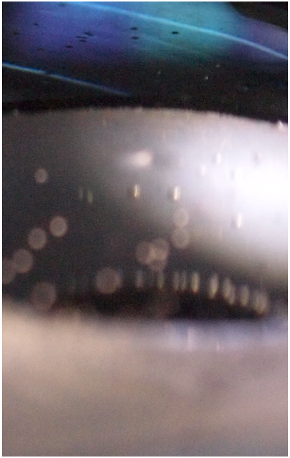
Main Loop

1. Form mound
2. Delay for a time
3. Send echo pulse
4. Record time taken to receive echo pulse
5. Increase delay duration
6. Repeat

- Repeated 90-150 times depending on resolution desired
- Delay times spaced logarithmically from 0.0001 to .3 seconds

Main Loop - Mound Formation

- Focused acoustic beam emitted at surface of liquid
- Surface absorbs absorbs some energy and starts to rise



Main Loop - Delay & Echo

- Time of flight of echo signal determined
- Waiting for a delay allows time resolution
- Changing the delay will measure the height at different times after the mound formation begins

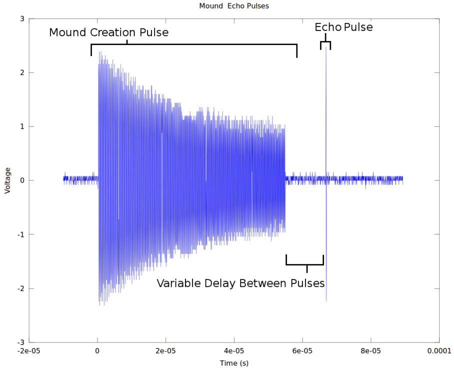
Main Loop - Record Data

- Echo Pulse recorded to computer
- Afterwards, computer extracts time of flight and other information

- Push a button and get coffee
- Rinse and Repeat

Behind the scenes

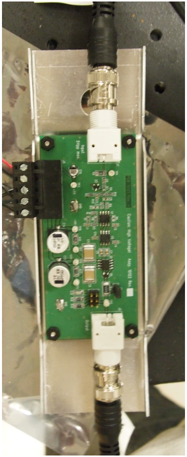
Signal Generation



- Mound creation pulse — 60 - 500 μs duration, 2.5 - 7 MHz toneburst
- Variable delay — 0.01 - 300 millisecond duration, changed at each iteration to allow time resolution
- Echo Signal — Single sine wave pulse

Amplification

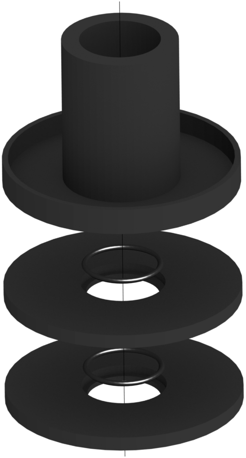
- Signal amplified to 98 V_{pp}
- Rail to rail switch pulser circuit



Transducer

- Either High Resolution or High Sensitivity
- Converts electrical pulses to acoustic pulses
- Receives acoustic pulses and converts them to electrical pulses

Bubbler

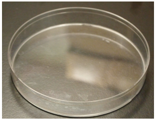


- Contains Coupling fluid
- Provides level base for fluid container
- Maintains constant contact between transducer and fluid container
- Double O-rings provide stability and sliding seal

Fluid Container

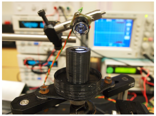
HDPE Bottle Cap

- Small and maneuverable
- Flat, firm surface
- Chemically Resistant
- Acoustic Impedance Mismatch with water



Polystyrene Petri Dish

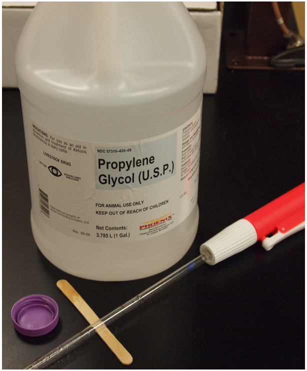
- Good acoustic power transfer with water
- Dissolved by many different chemicals
- Bottom tends to bow or flex



No Container

- Fluid directly on top of transducer in bubbler
- Conceptually simpler
- Fluid settle time into crevices
- No reflections

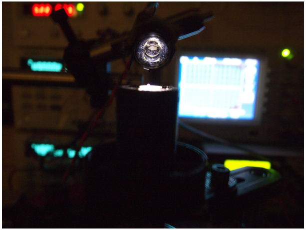
Fluid



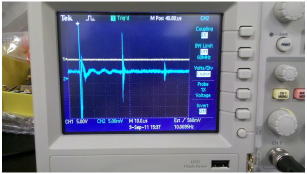
- Concentrations of propylene glycol mixed with water
- Watch for things in surface
- Watch for shear waves etc

Strobe light

- Variable delay from mound formation
- Variable duration



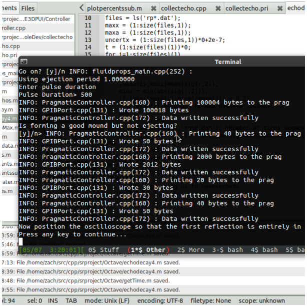
Oscilloscope Display



- Triggered to emission of echo signal
- Time of pulse on oscilloscope indicates time of flight

Control Software

- Generate signals
- Increments variable delay timestep and loops through experiment
- Acquires data from oscilloscope



```
files = ls('rp*.dat');
maxx = (1:size(files,1));
maxa = (1:size(files,1));
uncertx = (1:size(files,1))*0+2e-7;
t = (1:size(files)(1))*0;
for i=1:size(files)(1)
```

```
Go on? [y]/n INFO: fluidprops_main.cpp(252) :
Using ejection period 1.000000
Enter pulse duration
Pulse Duration> 500
INFO: PragmaticController.cpp(160) : Printing 100004 bytes to the prag
INFO: GPIBPort.cpp(131) : Wrote 100018 bytes
INFO: PragmaticController.cpp(172) : Data written successfully
Is forming a good mound but not ejecting?
[y]/n> INFO: PragmaticController.cpp(160) : Printing 40 bytes to the prag
INFO: GPIBPort.cpp(131) : Wrote 50 bytes
INFO: PragmaticController.cpp(172) : Data written successfully
INFO: PragmaticController.cpp(160) : Printing 2000 bytes to the prag
INFO: GPIBPort.cpp(131) : Wrote 2012 bytes
INFO: PragmaticController.cpp(172) : Data written successfully
INFO: PragmaticController.cpp(160) : Printing 20 bytes to the prag
INFO: GPIBPort.cpp(131) : Wrote 30 bytes
INFO: PragmaticController.cpp(172) : Data written successfully
INFO: PragmaticController.cpp(160) : Printing 40 bytes to the prag
INFO: GPIBPort.cpp(131) : Wrote 50 bytes
INFO: PragmaticController.cpp(172) : Data written successfully
Now position the oscilloscope so that the first reflection is entirely in
Press any key to continue...

[05/07  3:20:01][  0$ Stuff  (1*$ Other)  2$ More  3-$ bash  4$ bash  5$ ba
```

```
7:13: File /home/zach/src/cpp/srproject/Octave/echodecay4.m saved.
3:39: File /home/zach/src/cpp/srproject/Octave/echodecay4.m saved.
3:48: File /home/zach/src/cpp/srproject/Octave/getTime.m saved.
9:55: File /home/zach/src/cpp/srproject/Octave/echodecay4.m saved.
```

Analysis Code

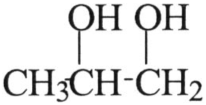
- Calculate time of flight from echo pulse
- Plot time of flight vs. Echo delay time
- Calculate mound height from time of flight
- Account for different starting fluid heights and evaporation.

Theory

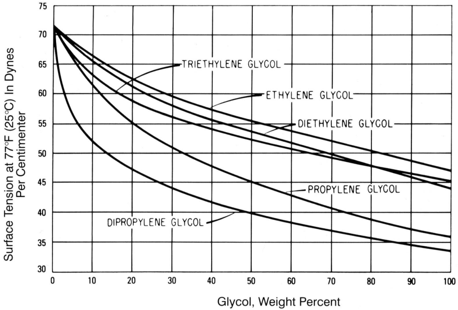
Key Concepts

- Energy Transfer (Electrical → Acoustic → Kinetic/Surface)
- Reflection and Transmission

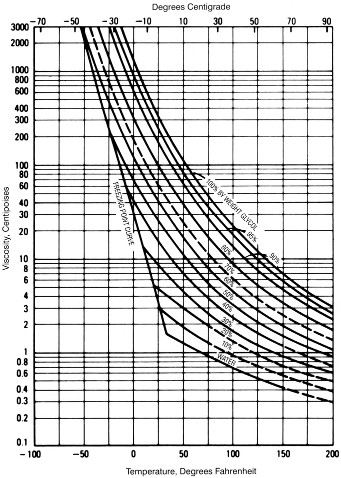
Propylene Glycol



$$\underset{}{CH_3}\overset{\displaystyle OH}{\overset{|}{CH}}-\overset{\displaystyle OH}{\overset{|}{CH_2}}$$



(Source Dow Chemical Company[6])



Acoustics

Input Power

Average Power for Repeated Sinusoidal burst

$$\frac{t}{T}\frac{V_0^2}{2R}$$

- **t** — duration of sinusoidal burst
- **T** — period of total pulse
- $\mathbf{V_0}$ — Peak to peak voltage across transducer
- **R** — Electrical Impedance of Transducer

Reflection at an interface

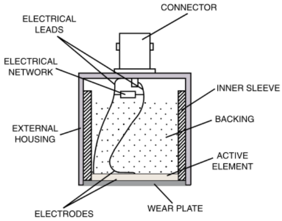
$$\frac{I_t}{I_i} = \left(\frac{Z_1 - Z_2}{Z_1 + Z_2}\right)^2$$

- $\mathbf{I_t}$ Transmitted intensity
- $\mathbf{I_i}$ Incident intensity
- $\mathbf{Z_1}$ Acoustic Impedance of source
- $\mathbf{Z_2}$ Acoustic Impedance of destination

Piezo Electric Transducer

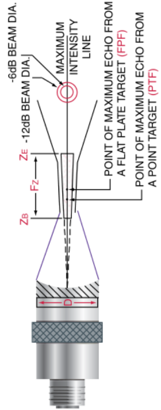
- Piezo crystal converts electrical impulses into mechanical vibrations
- and vice versa
- Backing provides damping for vibration
- Coupled to quartz rod

(Source NDT International, Inc.[7])

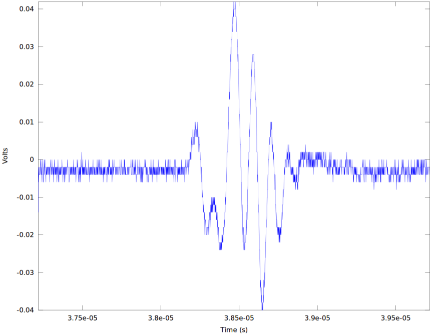


Piezo Electric Transducer - Focus

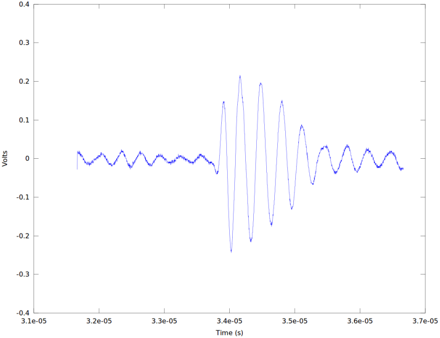
- Surface ground into partial sphere
- Focuses acoustic waves at focal point



Piezo Electric Transducers - Resolution Vs. Sensitivity



High Resolution — High Damping



High Sensitivity — High Gain

Ultrasonic Distance Measurement

Measurement for longitudinal waves:

$$h = \frac{\Delta t}{2} c$$

- **h** — Height of sound in medium
- **c** — Speed of sound in medium
- **Δt** — Time of flight of echo pulse

Fluid Dynamics

Viscosity

Tangential Stress Per Unit Meter

$$I_z = I_0 e^{-\alpha z}$$

$$\alpha \approx \frac{2}{3}\frac{\eta}{\rho}\frac{\omega^2}{c^2}$$

(Source Heuter and Bolt[3])

- $\mathbf{I_z}$ Axial acoustic intensity at z
- $\mathbf{I_0}$ Incident acoustic intensity
- η Shear viscosity
- ρ Density of fluid
- ω Wave frequency

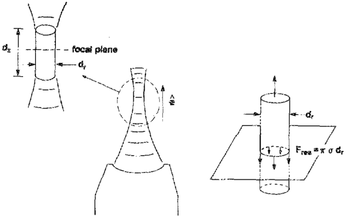
Surface Tension

$$\sigma = \frac{W}{\Delta A}$$
$$E = \sigma A$$

- Acts as a restoring force
- $A \approx$ size of focal spot

- **W** Work necessary for increased surface area
- **ΔA** Increase in surface area
- **E** Energy needed to create surface area A

Mound Formation



$$p_i = AP_L T = \frac{2AI_0}{c} = \frac{2E}{c}$$

(Source Elrod et al.[2])

- **p_i** Initial mound momentum
- **A** Area of mound
- **P_L** Langevin Radiation Pressure
- **I_0** Acoustic Intensity
- **E** Energy Density
- **c** Speed of sound in medium

Rise Time

$$t_r = 0.116\frac{2\lambda^{3/2}F^{3/2}\rho^{1/2}}{\sigma^{1/2}}$$

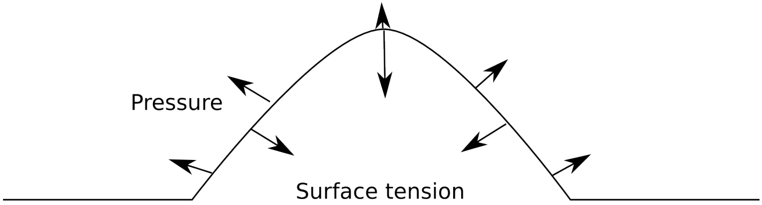
Or, solving for σ

$$\sigma = 0.0538\frac{\lambda^3F^3\rho}{t_r^2}$$

For water the current experimental setup, t_r is predicted to be $\approx 3900\mu s$. (Source Cinbis et al.[1])

- $\mathbf{t_r}$ Time for mound to reach maximum height
- λ Wavelength in fluid
- **F** F number of transducer $(\frac{FocalLength}{Diameter})$
- ρ Density of fluid
- σ Surface tension of fluid

Relaxation



- Pressure from acoustic waves initially propels mound upward and outward
- Surface tension and gravity bring mound back to flat surface

Maximum Height

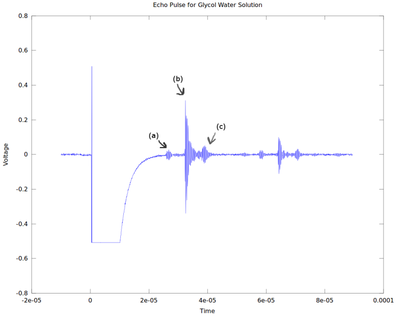
$$h_r = 0.21 \frac{E^2 f^4}{c^6 \sigma \rho}$$

(Source Elrod et al.[2])

- $\mathbf{h_r}$ Maximum height of mound
- **f** Frequency of acoustic toneburst
- **E** Incident energy of acoustic toneburst
- ρ Density of fluid
- σ Surface tension of fluid

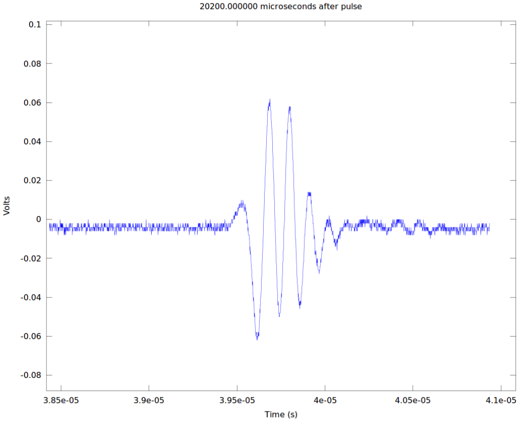
Results & Analysis

Echo Pulse Shape Analysis

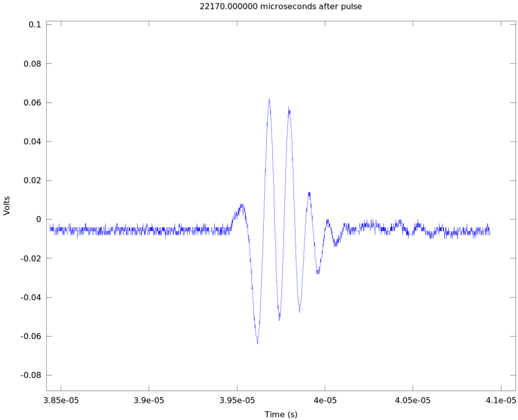


- a) Reflection from fluid container
- b) Reflection from fluid surface
- c) Second reflection from surface

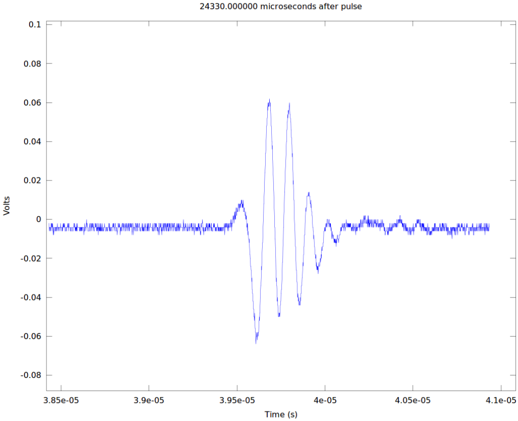
Successive Echo Animation



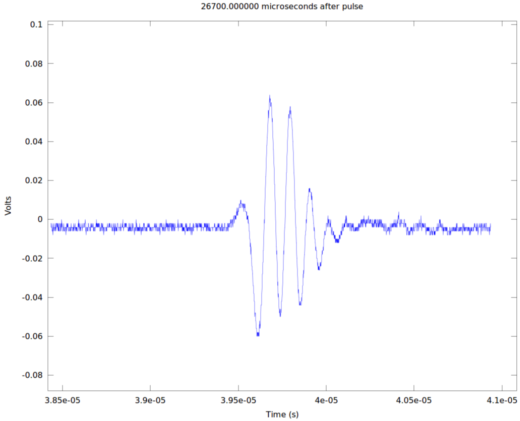
Successive Echo Animation



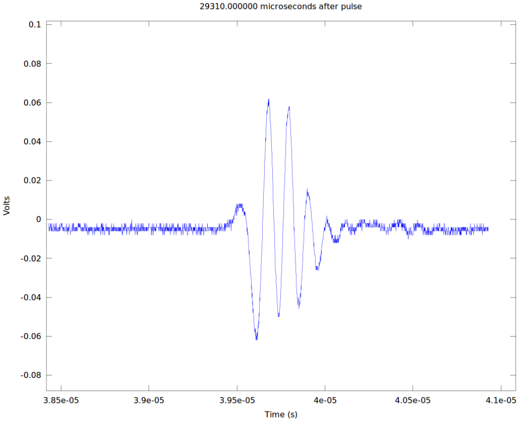
Successive Echo Animation



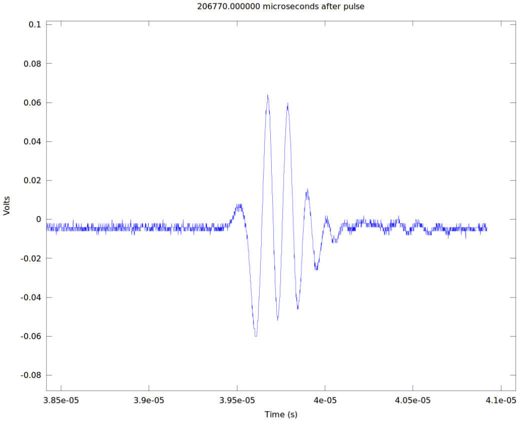
Successive Echo Animation



Successive Echo Animation



Successive Echo Animation



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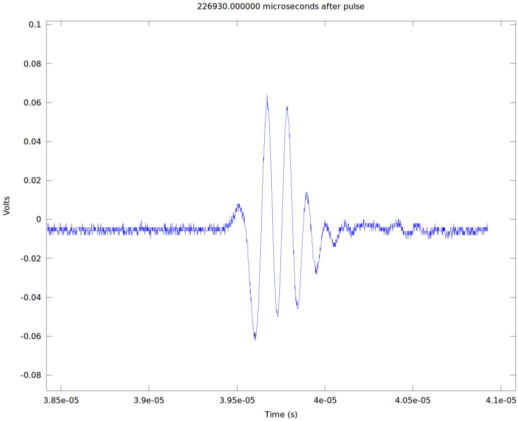

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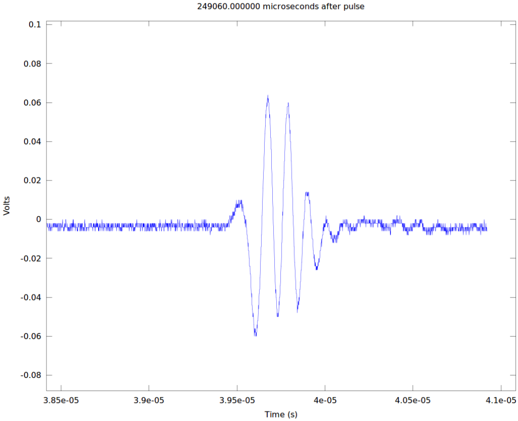
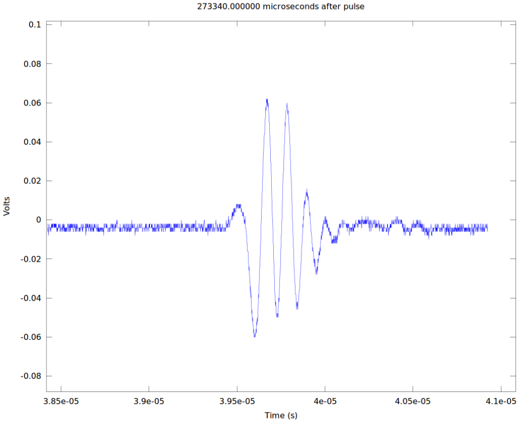
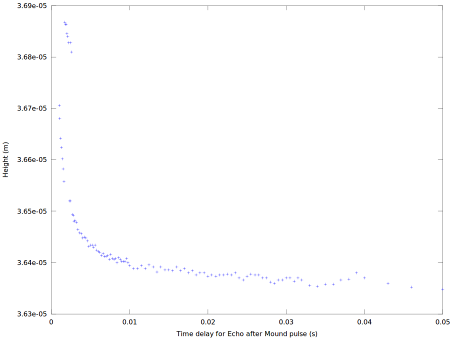


Successive Echo Animation

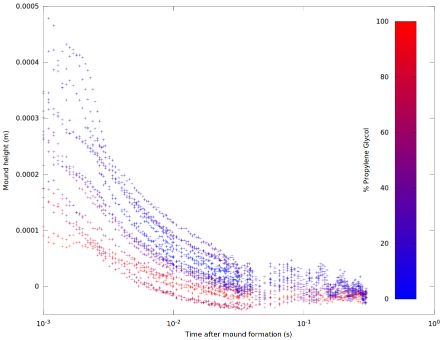


Relaxation Curve



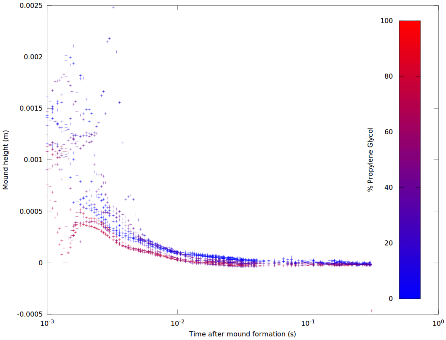
Mound Relaxation Curve for Pure Water

Non Container



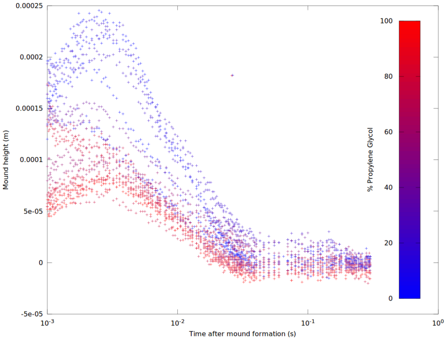
Log Scale mound relaxation for Solutions Directly in Bubbler

High Sensitivity Results



Log Scale Mound Relaxation for High Sensitivity Transducer in HDPE Milk Cap (2170 data points)

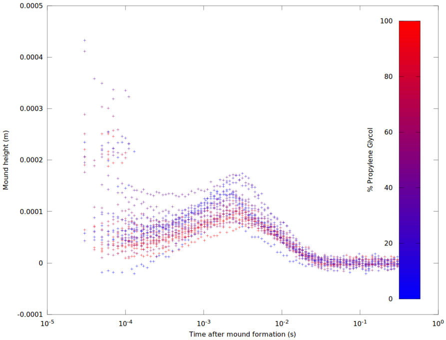
High Resolution Results



Log Scale Mound Relaxation for High Resolution Transducer in HDPE Milk Cap (3260 data points)

$\sigma \approx 140 \frac{\text{mN}}{\text{m}}$ (Expected $75 \frac{\text{mN}}{\text{m}}$)

High Resolution Results II



Log Scale Mound Relaxation for High Resolution Transducer in HDPE Milk Cap (2374 data points)

Future Work & Curiosities

Nuts & Bolts

- Faster Data acquisition
- Tighten precision on perpendicularity/levelness
- Better precision on mixing
- Better precision on transducer height
- Motorized transducer height
- Automatic Pipetting machine or bottle cap switcher

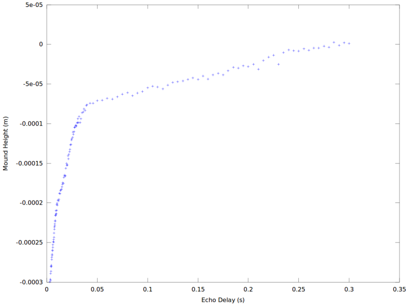
Theory

- Work out relation between emitted electrical energy, reflected and transmitted acoustic energy, HDPE container, and viscosity
- Determine relation between mound relaxtion rate and surface tension

Chemistry

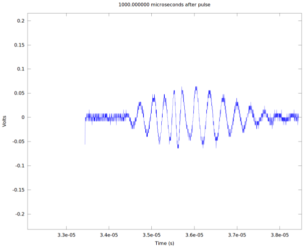
- Check fluids with lower viscosities and lower surface tensions
- Check fluids with higher viscosities and higher surface tensions
- Run experiments at different power levels and frequencies

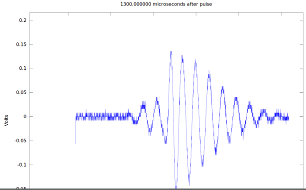
Inverted Relaxation Curve

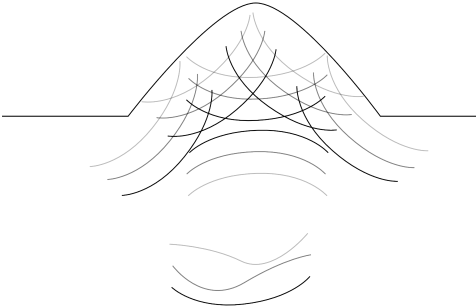


- Fluid seems to rise rather than fall
- May be due to standing vibrations
- May be due to alignment issues

Pulse Shape Shifting







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