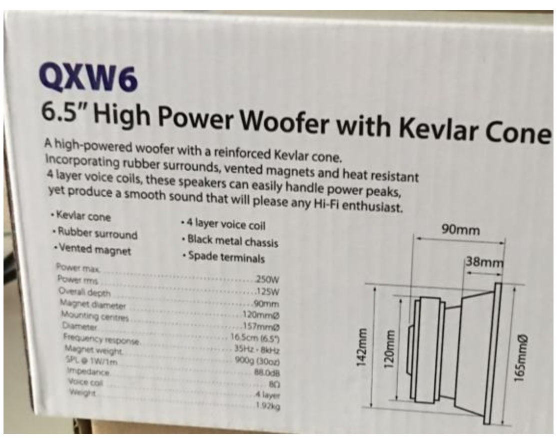
This extended report goes into further depth about the work carried out as part of the project. It includes more information about the thought processes that led to certain design decisions being made, and more in-depth analysis into data obtained as a result of the experiment. It is to be utilised as a guide for a deeper understanding of the project.

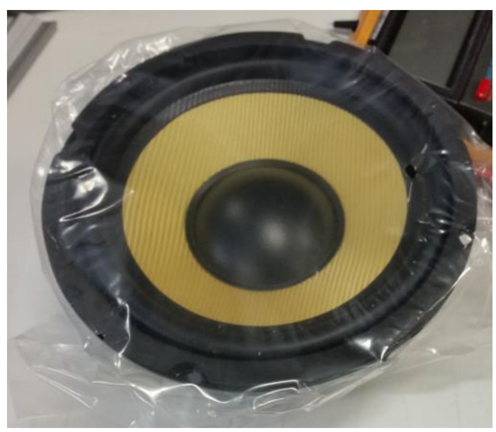
## Equipment

- **Speaker: QXW6 6.5" High Power Woofer with Kevlar Cone - QTX *1***
  - 250W power Max
  - 8Ω impedance
  - 1.92kg
  - 88.0dB
  - Frequency Response: 35Hz - 8kHz
  - Overall depth: 90mm; Diameter: 16.5cm
- **Liquids**
  - 1000 cSt Silicone Oil - From Derreck
  - 50 cSt Silicone Oil - Alfa Aesar, 63148-62-9, L05379
  - Fairy Liquid washing up liquid
  - Water
  - Sunflower oil - Sainsbury's
- **Recording Equipment**
  - Photron Fastcam SA1.1 Type 675K M1 ***7***
    - Input DC20-36V / 130VA
    - Resolution of 1024 x 1024 pixels at 5400fps
    - Maximum framerate of 675,000fps at resolution of 64 x 16
  - Lumix flash camera with GVaro 14-42 zoom lens 1:3.5 - From Kelvin Vine (Physics Film Makers)
  - Photron Spectrum Lumination P/N EL2150-WHI lighting ***8***
    - Manfrotto Photo Variable Friction Arm with Bracket, SKU 244
  - Smartphone cameras - Including IphoneX
  - Sony Cyber-shot RX-100 IV Camera, 4K, 20.1MP, 2.9x Optical Zoom, Wi-Fi, NFC, OLED EVF, 3" Tiltable Screen (1000fps camera)
  - Diffuser
  - High powered lighting - TriLite Max 3x30W Compact Flourescent Lamps 220-240V. Bowens, 3.15A (F)

- **Software**
    - Photron FASTCAM Software - PFV Ver.3681
    - Adobe After Effects CS6
    - Adobe Premiere Pro CS6
    - Adobe Illustrator
    - Google Sketchup
    - Sound Meter - Mobile App
- **Machinery - Institute of Making**
    - Lasercutter
    - Bandsaw
- **Signal Generators / Amplifiers**
    - Griffin Signal generator and Amplifier ***6***
    - ISO-TECH Synthesized Function Generator GFG2004
    - Hi-Fi Amplifier ELEGIANT Mini 20W 12V Hi-Fi Car Stereo Amplifier LP-838 ***2***
        - Kasstino Power Supply Adapter 12V AC 100-240V To DC 12V 2A 24W for LED Strips
- **Other:**
    - Cardboard Square
    - Circular plywood plate
    - 3.5” glass petri dish - from Chemistry (2nd Floor Turner Labs, Christopher Ingold) ***3***
    - 6” plastic petri dish - from Chemistry lab
    - Square tupperware box (135mm x 135mm)
    - LE LED USB Light Strip, SKU: 4100072-RGB
        - Power: 5W
        - 16 lighting colours
    - Optical Microscope
    - Soldering Iron & Solder
    - Plastic strips - from plastic binder
    - Plastic Pipette (1mm & 3mm) - from Chemistry lab
    - Digital Thermometer - 2000T - Thermometer, -200°C to +1350°C, 155 mm, 67 mm, 40 mmType Input, Intrinsically Safe
    - Multimeter
    - 3mm Laser grade plywood
    - Red Food Colouring

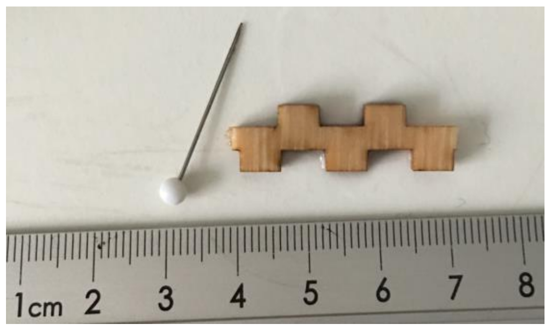
        - ASDA Natural Food Colouring - Red
        - Dr Oetker Bright Red Gel Food Colour 15g
    - Electric cables
        - BNC cables
        - Banana plugs (amplifier to speaker)
        - 3.5mm jack to aux (laptop to amplifier)
    - Double sided tape
    - Plastic & Glass Syringe - From Andrew Redfearn
    - Spray duster - Dataflash, DF1270
    - Knitting Needle ***5***
    - Wood cuttings
        - Grated cuttings - leftover from laser cutting ***4***
        - Solid blocks - from IoM
    - Foldback clips (clamps) - Q-Connect, 42mm
    - 1mm graph paper - Chartwell, A4-641C
    - Superglue - UHU
    - Metal ruler - 30cm
    - Crocodile Clips






***1*** Speakers used to drive liquid


***2*** Hi-Fi Amplifiers used to boost signal




Left: ***3***, 4” Glass Petri Dish used for the majority of the experiment

Right: ***4*** Tools used to create droplets, placed next to a metal ruler for scale


***5* Griffin Signal Generator & Amplifier**


***6* Ultra High Speed Photron Camera**


***7* Ultra High Speed Lighting**

Report style starts

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## Experimental Method

This section fully explains the processes undertaken in this project. It includes the descriptions of the personnel involved, expenditures and relevant venues.

*1. Sourcing of equipments*

Researching of possible apparatus to construct the preliminary prototype has been conducted through online search and reading of peer-reviewed papers. A list of equipments was compiled, with prices and links to purchase. This was partnered with alternative options as backup, in case if there is time concern, budgeting issues or extensions to experiment. Due to the limited budget of £200, it was decided that the team will try to source as many equipments freely as possible, considering that around £40 had to be set aside for poster printing.

The following steps were taken by our team in self-sourcing of equipments. This was to gain knowledge on certain equipments, borrowing them or seeking further assistance.

A. Spoke to the Mechanical Engineering department on the 5th floor of Roberts building. The people advised us to order an 'off the shelf' amplifier. They were able to provide us with a 3.5mm jack to aux cable.
B. Spoke to Mychal Riley from Mechanical Engineering regarding high speed camera. He provided us with a contact - Dr. Han Wu from 224 Chemical Engineering, who possesses a high speed camera and might be able to assist us.
C. After further exploration of the offices on the 4th floor of Roberts building, a person referred us to Andrew Redfearn, who might have equipments for professional video capturing.
D. Spoke to the owner of a camera shop near Tottenham Court Road station - Parl Cameras: Rathbone Pl, Fitzrovia, London W1T 1JR
E. Borrowed petri dish (4") from the Chemistry department: Turner Lab on the 2nd floor of Christopher Ingold building.

The central piece of equipment was the speaker. In order to obtain the desired power, dimensions and function, it was compulsory to purchase using our budget. It was decided that online purchases should be carried out with Amazon Prime due to its next day delivery service. The speaker was ordered from the following link:
https://www.amazon.co.uk/Powered-Woofer-Aramid-Fibre-Driver/dp/B01G8TUQ14/ref=sr_1_6?ie=UTF8&qid=1516194867&sr=8-6&keywords=6.5+inch+woofer

It was determined that for mobility and commercial purposes, the speaker should be secured in a box which will create a self-contained system. The box must be strong enough to withstand the mass of the speaker and the force created by the vibration of the speaker. Through further research, it was decided that the box can be created with plywood through laser cutting. UCL has a laser cutting, which is situated within the Institute of Making (IoM). The team went down to IoM to discuss the creation of the 3D box with the supervisor, who was kind enough to permit us with the operation of the laser cutter. With that, the team purchased a piece of 3 mm laser-grade plywood. The box was assembled by laser cutting each side of the box with fingerjoint edges.

The next step involves placing the speaker into the box. It was found that the depth of the box was slightly miscalculated, where the edge of the speaker was not in contact with the box. This was compensated using spare pieces of wood joints from the by-products of laser cutting. The assembling can be seen in Fig. 8:

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Report style ends. Below are the steps in point form.

**Processes** (include people involved, any money spent, places visited etc..)

1. Research equipment needed for first prototype and order parts where necessary whilst trying to source as many things freely as possible
    a. Spoke to Mechanical Engineering - they advised we order an ‘off the shelf’ amplifier and gave us a jack cable (5th floor)
    b. Spoke to Mychal Riley in Mechanical Engineering - He gave us the name of ultra high speed camera person - Dr. Han Wu Office 224 in Chemical Engineering Dept.
    c. Knocked on random door on 4th floor, got referred to Andrew Redfearn
    d. Researched oil types & viscosities & slo-mo cameras. Spoke to camera shop near TCR station - Parl Cameras:  Rathbone Pl, Fitzrovia, London W1T 1JR
    e. Borrowed petri dishes from Turner lab, 2nd floor Christopher Ingold.
2. Compiled a list of equipments, with prices and links to purchase. Also included alternative equipments to consider, in case of issues of budget, time, extensions to experiment. Refer to appendix.
3. Ordered:
    a. Subwoofer: https://www.amazon.co.uk/Powered-Woofer-Aramid-Fibre-Driver/dp/B01G8TUQ14/ref=sr_1_6?ie=UTF8&qid=1516194867&sr=8-6&keywords=6.5+inch+woofer Consideration: diameter, depth, power, price
4. Went and discussed 3D box with Institute of Making (IoM), they were kind enough to allow us to use the lasercutter. We bought a length of 3 mm lasergrade plywood and laser cut out a box with wooden fingerjoints

5. Assembled the box and tested by placing speaker inside, it was too short. Compensated with plywood placeholders (offcuts) so the speaker fit inside ***8***

***8* Loudspeaker placed inside Lasercut plywood box with fingerjoints, the speaker was too high hence wood offcuts were used to hold the speaker in place**

6. Tested the subwoofer with iso-tech and griffin signal generator and amplifier. The power output was low and petri dish not very well connected. First tested was 1000 cSt Silicone oil. Managed to produce a droplet that lasted for a few seconds but there was no movement as this was too viscous.
    a. A frequency range of 50 - 100 Hz was tested

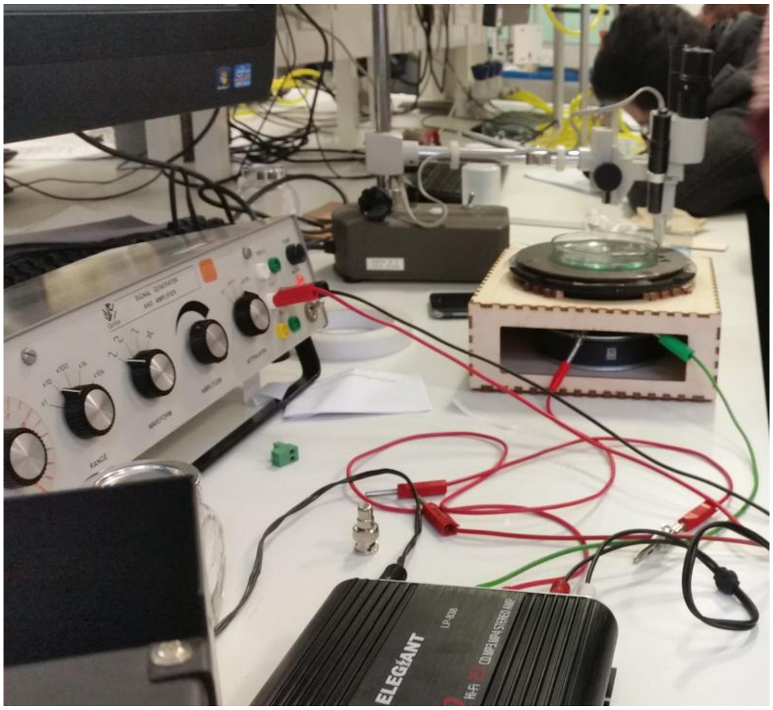
b. Decided to use double sided tape to stick the square cardboard plate onto the edge/diaphragm intersection and then sticking the petri dish onto the cardboard because we did not want to damage the diaphragm. However the concern was whether the cardboard plate can fully transmit the vibration of the speaker. Sticking the petri dish onto the diaphragm was considered the final resort.
    i. 4 mm of 1000 cSt silicone oil was poured into the 4" petri dish. Throughout the entire experiment, only the 4" petri dish was used, perhaps it may be a good idea to test the larger one. Although it was deemed this was actually 3.5" later on
    ii. Also used the needle to stimulate droplets. The high viscosity of the silicone oil made it difficult to fall from the needle, even after rigorous hammering.
        1. It was difficult to actually create droplets with such a high viscosity, different methods were attempted including releasing droplets from a low height. Smaller liquids were seen to have survived longer
        2. Drops were created although were not sustained for long before coalescing with the liquid.
        3. The droplet appeared to be sitting on the surface of the liquid instead of bouncing.

c. The maximum amplitude was deemed too low hence drove the decision to purchase an amplifier:
    i. https://www.amazon.co.uk/ELEGIANT-Stereo-Amplifier-Channel-Output-Black/dp/B018U98RC0/ref=redir_mobile_desktop/260-0925782-8402561?_encoding=UTF8&keywords=audio%20amplifier&pi=AC_SX236_SY340_QL65&qid=1517209521&ref_=mp_s_a_1_12&sr=8-12 Consideration was its delivery time due to Amazon prime.
    ii. Power cable https://www.amazon.co.uk/Sunydeal-charger-Adapter-Adaptor-Monitors/dp/B015PZ33SU/ref=sr_1_1?s=electronics&ie=UTF8&qid=1516199409&sr=1-1&keywords=Replacement+60W+12V+5A+Adapter+Charger
d. Decided that the square cardboard plate had to be scrapped due to its lack of rigidity and air escaping the side which meant energy wasn't being driven into the fluid.

i. This was replaced with a circular 3 mm plywood cutout which was of slightly too small diameter. However this was just large enough to be secured with tape, although not ideal.
    1. If the wooden plate was not secured properly, large sound waves would manifest itself through the liquid. At higher amplitudes, the plate need to be hold down with hands.

7. Returned to chemistry following this and obtained a less viscous version of Silicone Oil. 50 cSt from Turner Labs.

8. With the new laser printed box and amplifier, 50 cSt Silicone oil was driven at 60-80 Hz. As an improvement, the circular plywood cutout was used as the rigid base, fixed with tape. Achieved bouncing droplets that were sustainable for minutes.
    a. The amplifier was wired to the speaker and mobile app, increasing the volume output and allowing the bass and treble to be manipulated. High volume and bass were found to be beneficial for producing high bouncing droplets. It was analyzed that our frequency range corresponded to bass, thus the two knobs work similarly.
        i. The amplifier was powered with a 12V, 1.2A plug although it could handle 2.0A. Though this was sufficient for sustainable droplets, some of which combined together to form larger droplets and / or interacted with each other
    b. Other than using a mobile phone, a lab signal generator was also used.The device was set to minimum attenuation and 4 ohms impedance to match the impedance of the speaker. This maximizes the signal transmitted. The set-up is shown in Fig. 9.
    c. Due to the lack of correct connectors, a self-made wiring system was created using soldering.



***9* Image of the initial set-up in laboratory 1, the petri dish was held down by double sided tape. It is visible here that the amplifier has been connected**

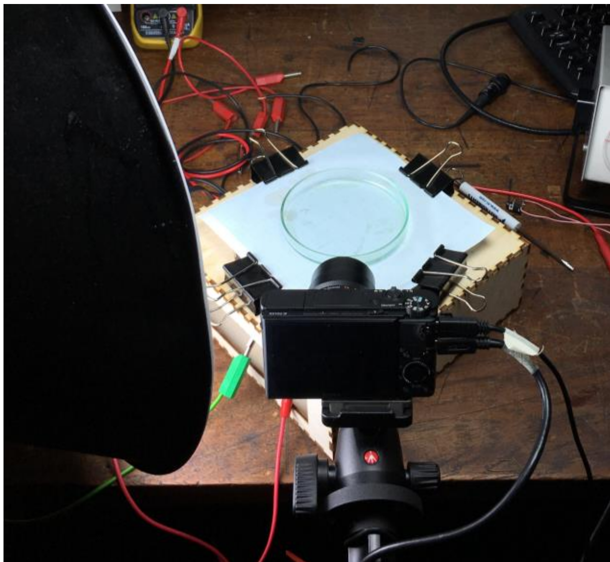
9. Eventually a ‘walking’ droplet was observed, although it was uncertain whether this was due to it actually walking or an external force. The phenomena occurs when the droplet is incident on the crest of its own wave and bounces up with a resultant horizontal momentum. It was also possible to combine droplets together, forming crystal lattice.
    a. Droplet behavior and motion was captured with the slow-mo mode on iPhone. It was found that the droplet size was too small to be accurately determined by the naked eye or through a photograph. Considered viewing the droplet through a microscope.
        i. Borrowed a microscope from Physics lab 3. However it was difficult to operate so this idea was not developed further.
        ii. Decided to tape graph paper underneath the droplet to track motion and size.
            1. Try to track the amplitude using software from video obtained
            2. Quantitative method to record data
        iii. Fix petri dish without seeing the tape.
    b. Since the circular plywood cutout was only taped down, it is not fully secured so it had to be held down. This suggested that clamps can be used to secure. Hence the decision to buy foldback clips:

   i. https://www.amazon.co.uk/Q-Connect-42mm-Foldback-Clip-Pack/dp/B000KJO7LO/ref=sr_1_2?srs=1651782031&ie=UTF8&qid=1517517805&sr=8-2&keywords=foldback%2Bclip&th=1 Consideration: size and quantity
   ii. The size of the circular plywood cutout was found to be smaller than the diameter of the speaker edge. This may prove to be difficult to secure down. Considered to recut the circular plate from leftover plywood.
c. After observing basic phenomena, an attempt on double-slit diffraction was done with improvised grating - a leftover plywood edge piece. An attempt to submerge the grating created droplets of considerably larger sizes and often multiple droplets at once. This became the new method of creating droplets.

10. Contact was made with Andrew Redfearn, a PhD Engineering student who kindly agreed to let us use his digital camera (50 fps) and setup in his laboratory to try and record some footage - Roberts UB54
    a. Experimentation was conducted in a dark room. His setup included 2 sets of powerful lighting and a trigger prompting 2 s of recording which was relayed to a computer monitor as shown in Fig. 10 to 12.
       i. Though the focus was difficult, recording of droplets was achieved at regular (25 fps) and high (50 fps). Although the droplets had to be towards the edge of the petri dish as the focus of the camera was limited here
       ii. Interestingly, the droplet bounce itself was refracted through the glass and waves were better observed on the side of the petri dish once the slo-mo footage was reviewed
       iii. High speed recordings were made as the frequency was varied from 50- 80 Hz. It was found that droplets were stable at 50 Hz
       iv. As lighting was an issue, it was suggested a polaroid / diffuser be used. One polaroid was attempted although it made little effect
    b. Graph paper was put underneath the petri dish to get an idea of scale of the droplet, these were found to be ~1 mm in diameter. The graph paper was clamped together with the circular plywood cutout onto the speaker edge.
    c. Our initial setup using the signal generator did not produce a detectable input by the amplifier.

    i. Upon investigation, Andrew pointed out an interesting point, the device may not have been grounded correctly so may present a large safety issue where the common grounding voltage is different across components.
    ii. Upon switching to a mobile device using a website signal generator, the input was detected and the experiment proceeded.

d. It was observed that the droplets tend to move towards one side which was not caused by the "walking". This was later found out during dismantling that due to the size of the plywood cutout, it did not rest leverly on the speaker. This prompted the need for a proper sized circular plate.
    i. To overcome that temporarily, a thin piece of wood was slided underneath the box.
    ii. A suspected cause was dirt or debris within the fluid which the droplets may have gravitated towards.
    iii. Another was the uneven level of the tabletop. Although eventually the fluid was tilted to push the droplets to one end within the focus of the camera. This was done by placing a small block underneath the opposite side of the speaker to lift it slightly thus creating a small incline.



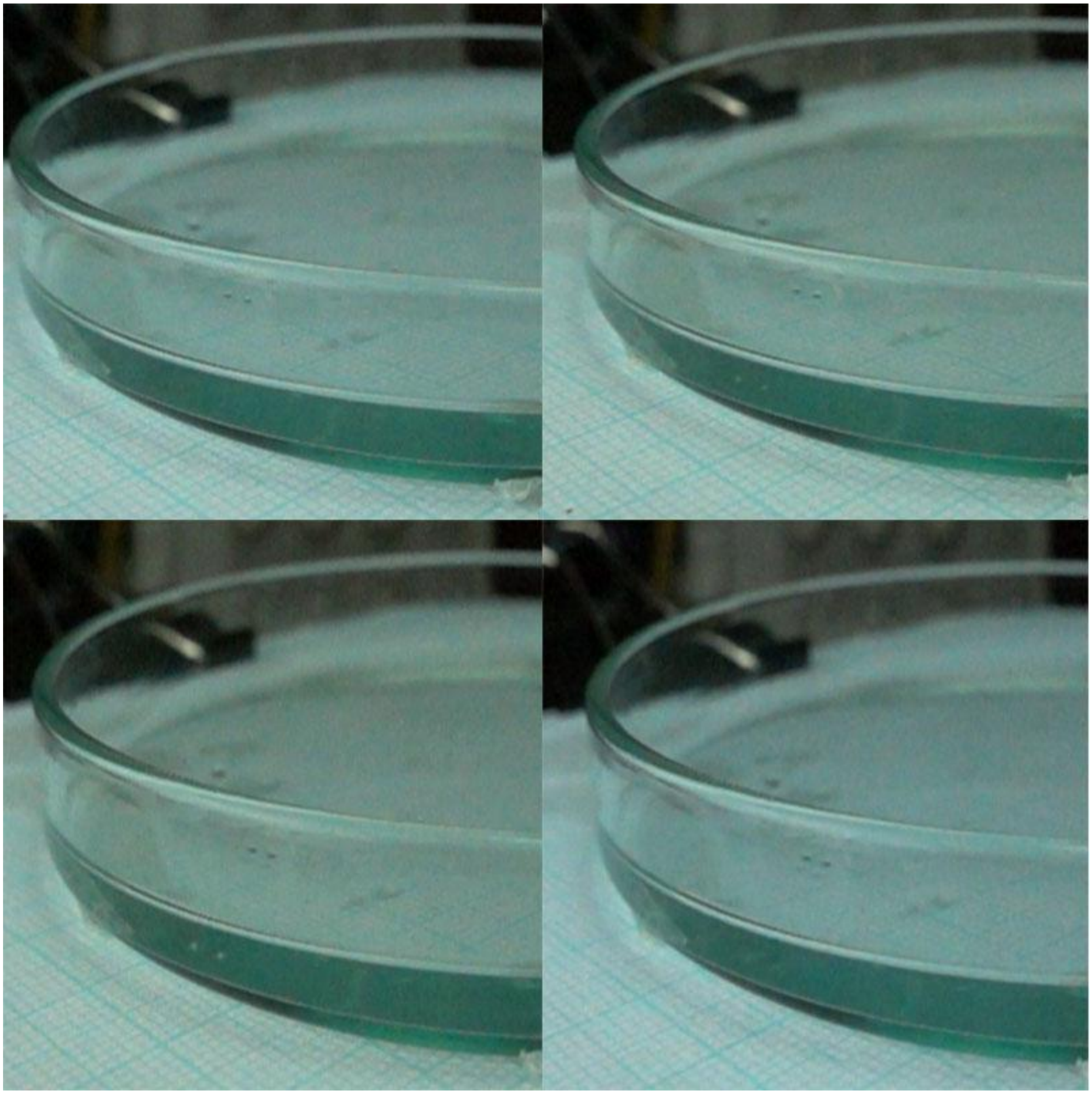

***Left to Right***

***10* Photo of the set-up behind the camera, this was for side shots to capture vertical motion.**

***11* Photo where shots of droplets were taken from top-down view. High powered lighting was necessary as regular lights flicker at 50 fps (flicks per second)**

***12* The camera was connected to a trigger and the video displayed on a computer monitor**

11. Following this, analysis was carried out using Adobe After Effects where the camera frame-rate was found to actually have been set to 50 fps. Therefore any recorded effects would have been an example of the stroboscopic effect
    a. The initial predictions from research papers was that the bouncing amplitude is not constant, every other bounce will be lower in amplitude.
    b. With a large number of video clips recorded, the one that was chosen gave a good account of the vertical motion of the bouncing droplet, refer to Fig. 13.
    c. The steps are as follows:
        i. Creating a new null object to store the data of droplet coordinates
        ii. Using the Track Camera, locate the region to track and then analyze the clip.
        iii. Apply the results to the null object.
        iv. Select all keyframes and paste in notepad.
        v. Plot in Excel.
    d. The results showed a stable oscillatory motion, with every second peak lower than the first.
    e. Tried to quantify amplitude, but restricted by our knowledge of relative size of the droplet with respect to resolution.
    f. Tracking results will be explored further later during the analysis of high speed captures.

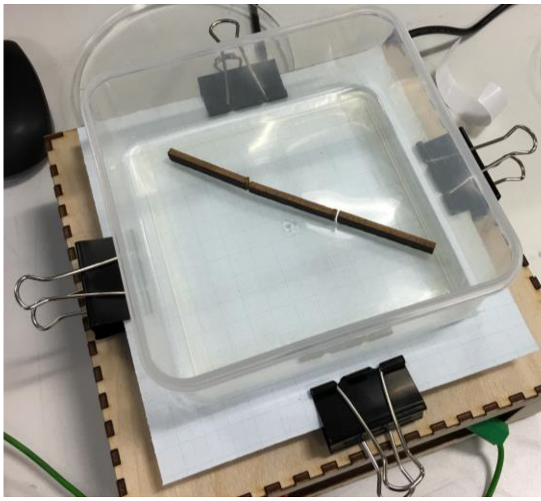
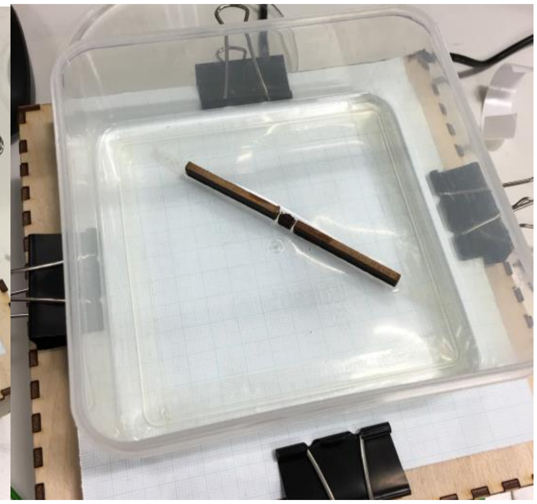


***13* stages of bouncing droplet for a digital camera, here we discovered that the ripples (waves) produced by the bouncing droplets could be observed on the side of the petri dish from refracted light**

12. Back in 1st year teaching labs (Physics department), attempts were made at quantifying properties of a bouncing droplet, such as their sizes and amplitude. It was also attempted to observe walking and repelling pairs and obtain a notion of their acceleration
    a. A note of the temperature was taken (it felt particularly cold) as this may have had an affect on the viscosity of the oil droplets

    i. It was suspected this may have resulted in it being difficult to create and maintain droplets, although another reason may have been the depth of the oil
    ii. Droplets would simultaneously pop, making it difficult to quantify measurements
  b. Droplets were made with a 1 mm pipette after realising droplets made using a 3 mm pipette were too large and did not bounce
    i. The shadows were projected on the graph paper when illuminated from above, this was used to obtain an estimate of the size of the droplet, although this is subject to a parallax error with the best illumination being from directly above
  c. A series of measurements were made at different distances for a set noise. A standardised distance of 30cm was set and the dB was recorded using a mobile sound app. The volume was controlled using the computers in laboratory 1
    i. Having the volume controllable using the computers meant that a quantity could be assigned to it rather than just a setting on the turnable knobs on the Hi-Fi amplifier
  d. It was eventually decided due to difficulty in trying to quantify measurements, it would be better to attempt to observe and record phenomena instead this was deemed a path of greater success given the timeframe for the experimental project

13. The next day, we returned with a wooden circular plate of size equal to that of the speaker diameter and so could be secured firmly with just clips. Again a temperature measurement was made of the room (18.9 +/- 0.1)degree C.
  a. An attempt at heating up the silicone oil was made by placing it near the heat sink of a laptop, although it is likely this only made a small impact, a better solution in the future would be perhaps to place it in a warmer place for storage or heat up the room
  b. A square tupperware box as shown in Fig. 14 was also attempted with square slits of wood to attempt diffraction (the slits acted as gratings)



***14.1* Square tupperware container used with double slits made from spare wood pieces, it was found that the silicone oil would adhere to the sides of the wood due to surface tension creating a steep wall**

***14.2* Double slit with closer distance as we realised the one shown in *14.1* had slits too far apart**

i. Initially the slit was too narrow for droplets to travel through, so it was eventually expanded

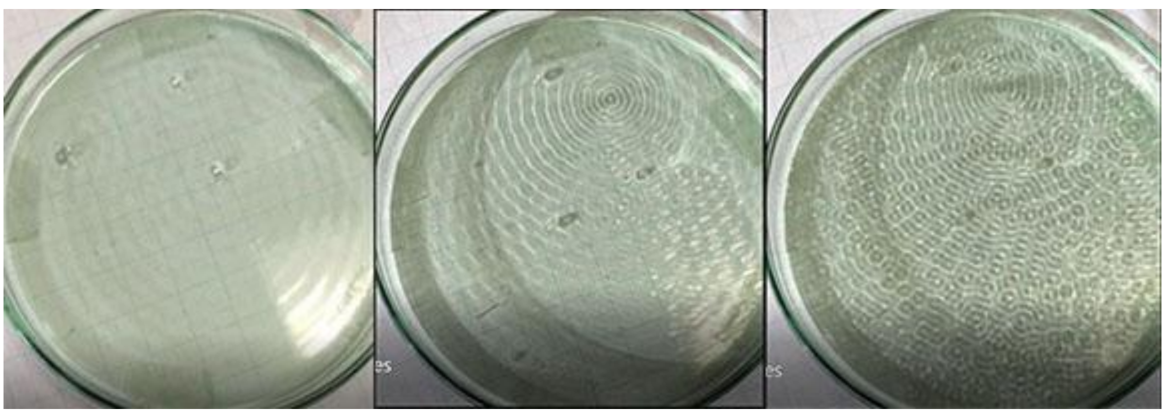
ii. It was found that the 50 cSt silicone oil would crawl up the slit due to surface tension and create a sort of barrier which prevented the droplets from interacting with the barrier and would instead interact with the oil layer coating the barrier

   1. A tested solution to this was to submerge the slits and pass the droplets through
   2. Although droplets were made to travel through the submerged slits, no diffraction was observed.
      a. Note droplets were forced through by applying a force to them using compressed blown air, pushing with a stick and tilting the set up
      b. It was not helped by the fact that the tupperware container bottom was non-flat and so it was decided to revert to the petri dish.

iii. Eventually the experiment was simplified and reverted to a singular slit in order to test diffraction using the round petri dish, both submerged and non-submerged slits were tested.

1. The same issue was encountered regarding surface tension of the slits, again no diffraction was observed with the naked eye.

14. With most testing done, it was decided that a different type of liquid to be tested. This time the experiment was carried out with soap water because of how easily accessible it is. Some papers have used soap water as well, and it will be a good alternative if the project were to be commercialized or brought to a school. The other candidate shortlisted was vegetable oil.
    a. The soap solution was produced by mixing some washing up liquid and stirring it with a wooden stick. The amount used was such that there was a visualizable green tint.
    b. The system was again driven at 50 Hz which easily produced droplets. It was found that waves were much more visible with washing up liquid (including standing wave). Under a certain angle, waves produced by droplets were clearly visible under ambient light.
        i. Faraday instability regime was featured by a sudden increase in volume and chaotic waveforms on the surface. This was clearly visualized using soap water as seen in Fig. 15.



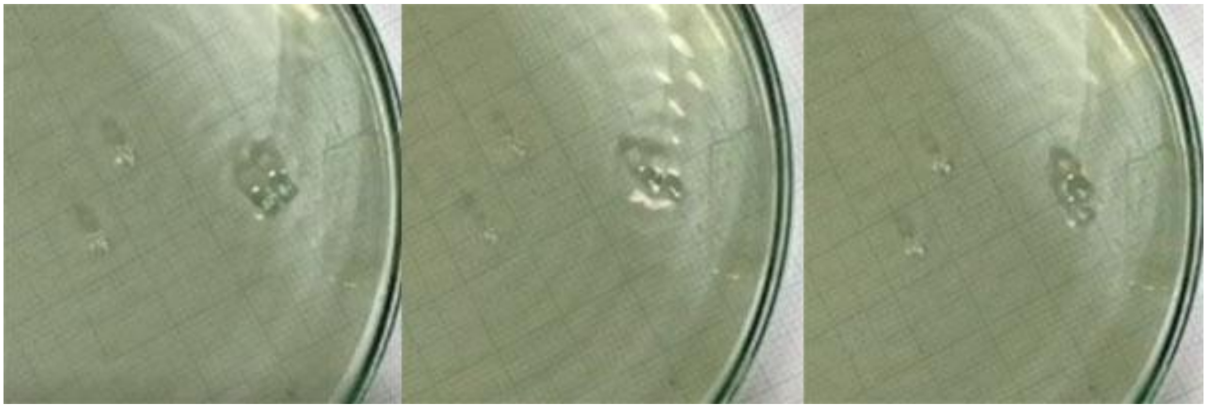
***Left to Right***

***15.1* Standing wave formed by bouncing droplets**

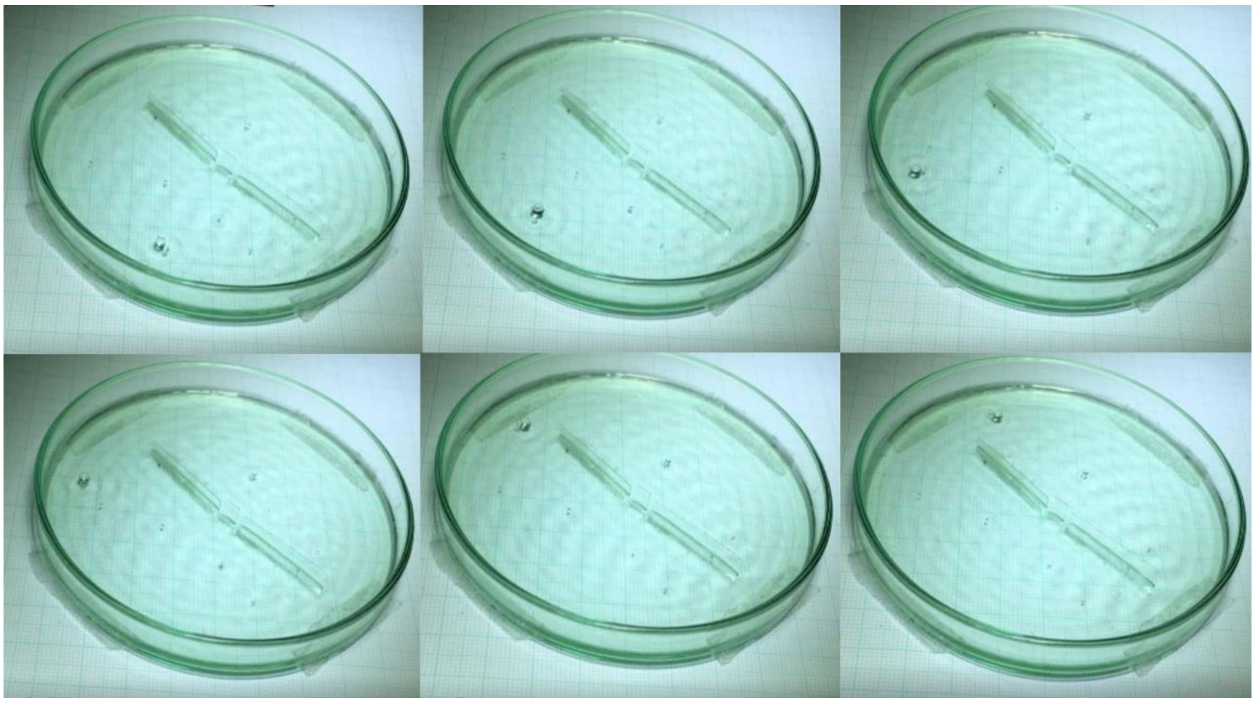
***15.2* Increasing volume to the boundary of Faraday threshold, surface starts to break**

***15.3* Faraday regime where droplets have a chaotic motion**

        ii. Observed and recorded standing waves, walking and orbiting phenomena, where a orbiting pair can be seen in Fig. 16 and a walking droplet in Fig. 17.



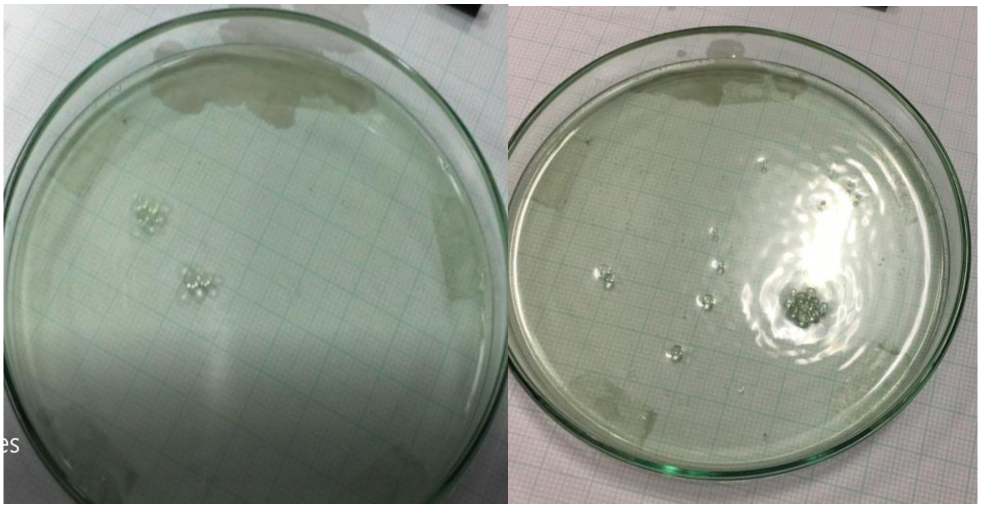
***16* Orbiting droplets observed interacting with each other**



***17 left to right* Using a regular camera, one large droplet was clearly observed 'walking' around the perimeter of the petri dish. Also here, washing up liquid was used**

iii. Attempted single slit diffraction by blowing droplets through, eventually changed tactic to moving the slit to the droplet (relative motion). The difficulty of moving droplets through the slit was due to surface tension.

iv. Results of using soap water created more consistent droplets and more quantum phenomena observed. Observed a cluster that resembles a crystalline lattice, where three droplets formed a triangular lattice. This can be seen from Fig. 18.



***Left to right***

***18.1* An aggregate of three droplets, formed from the self-assembly of steady state bouncers into a cluster**

***18.2* A larger cluster of droplets. They did not form a regular crystalline lattice structure, but more like a random assembly. It was observed that droplets would tend towards each other regardless of their initial starting position**

c. Attempted to dye the liquid. The effect was not very beneficial as the liquid became more opaque. It did not really aid with visualization as seen in Fig. 19, but it was worth the try.

***19* Repelling quadruple observed. Soap water was dyed with red food colouring, but was found to be limited in enhancing the visualization.**

d. Thin slits of plastic was used to create the grating. With liquid already in the petri dish, it was not possible to glue or tape the slits down. So the slits were held by hand, but it decided that they will be superglued during the next session.

e. Considered improvements such as lighting (LED strips)

15. A high speed camera (capability up to 600,000 fps!) was rented from the Department of Chemical Engineering, supervised by Dr. Han Wu. This was accompanied with a pair of table attachable powerful lighting and a regular camera for recording at a normal rate (25 fps). A diffuser was also taken and finally a laptop with the software required to operate the high speed camera.
    a. Note that the ultra high speed camera only recorded in black and white
        i. An issue also faced was attempting to find the best angle and distance in order for the camera to have the best focus, positioning the spotlight and adjusting the aperture were necessary to better visualise the final image on the computer
    b. This time plastic slits were superglued to the petri dish in attempt at diffraction again with soap water - it was uncertain how the glue would have mixed with the soap. The slits are shown in Fig. 20.

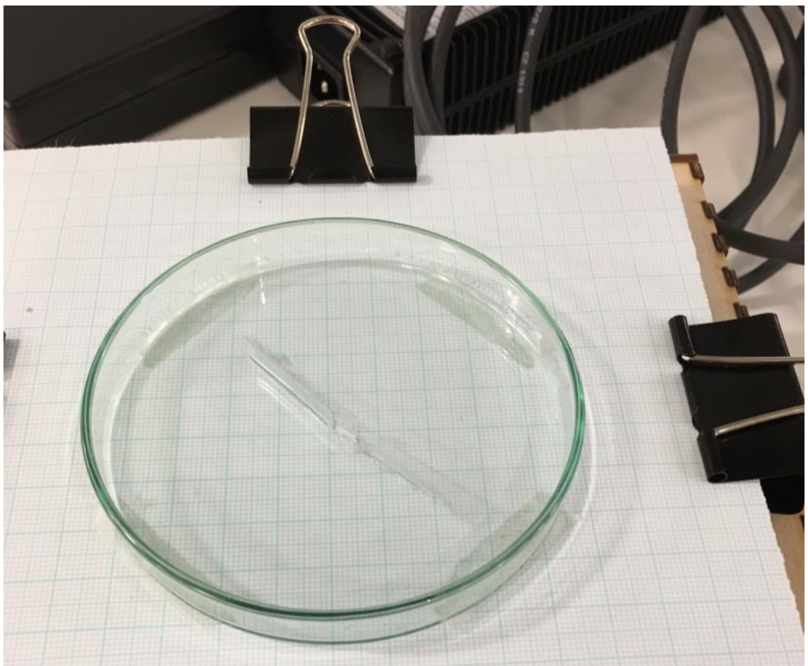
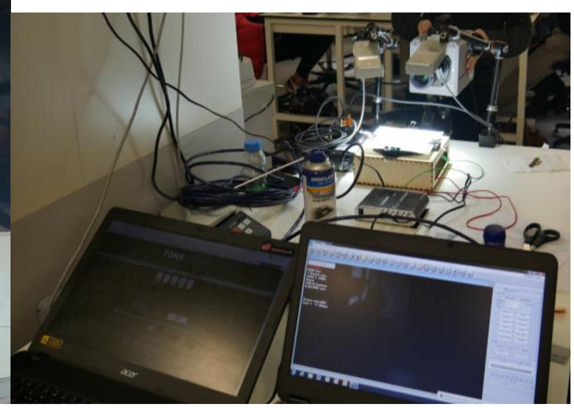


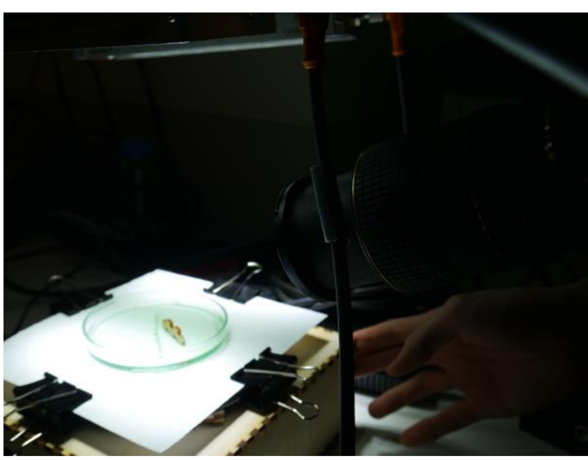
Fig. 20. Self-improvised double slit experiment, made with thin plastic sheets superglued to the bottom of the petri dish.

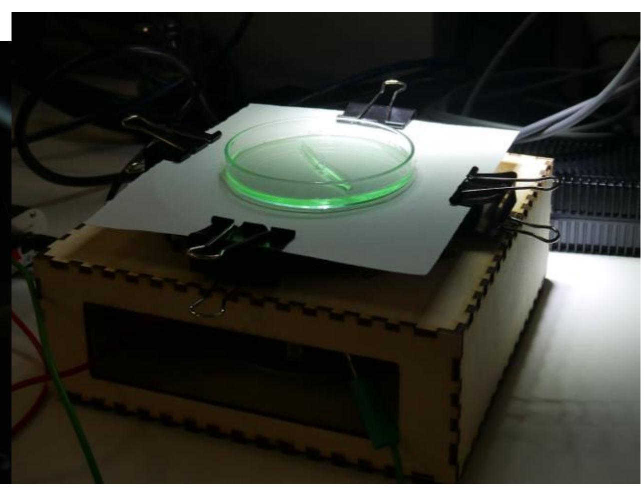
    c. Initially the frame rate was set to 1000 fps and resolution of 1024 x 1024, giving a video time of around 8 s.

i. There is a trade off between resolution and maximum framerate. For example the highest framerate at this resolution is 5400fps. Whereas if a higher framerate is required, the resulting video will be of lower resolution.

d. The trigger was controlled on the computer and other calibrations were also carried out in the software interface. The set-up can be seen in Fig. 21 to 24.







***Left to Right***

***21* Foreground: Regular camera on tripod on table to capture regular speed footage, background: Ultra High Speed Camera to capture high frame-rate footage of illuminated droplet**

***22* Two laptops used, the one on the left operated the website which set the frequency for oscillation and the one on the right allowed control of the software for the ultra high speed camera**

***23* Closeup of the ultra high speed camera lens**

***24* Closeup of the experimental apparatus being recorded**

e. The amount of light captured by the lens can be adjusted, where it is usually on the highest mode. But it was found that lowering it can help with visualization since there is already a pair of powerful lighting.

f. In high-speed mode, bouncing and walking were captured. The difficulty to produce other phenomena was due to the limited region that was focused. Sometimes the droplets had to be forced into the focus and often caused them to break.

   i. Individual wavefronts were clearly visible as seen in Fig. 25.

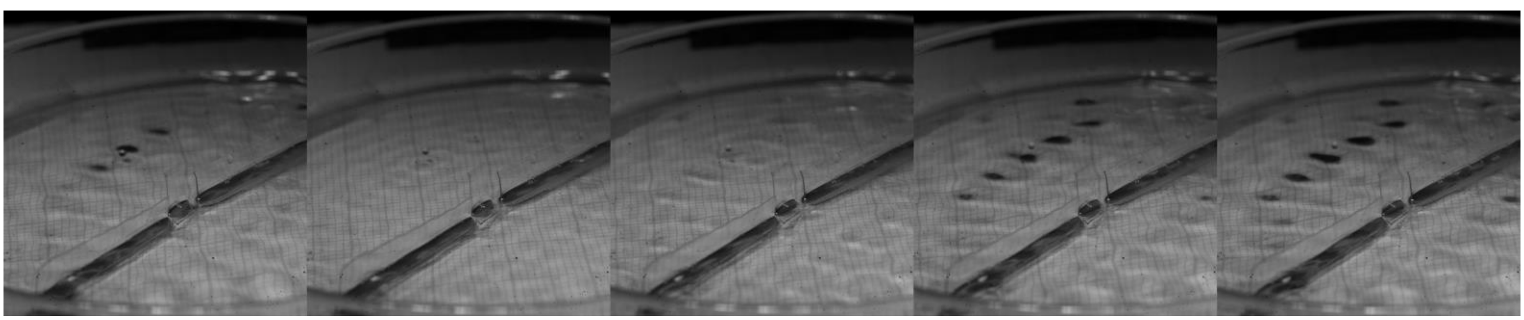
   ii. Tried to observe the interference of droplet waves with slit. Also tried to continuously create waves and observe their interaction with the slits.

   iii. Produced multiple droplets and observed their interactions with each other and with the surface as seen in Fig. 26.

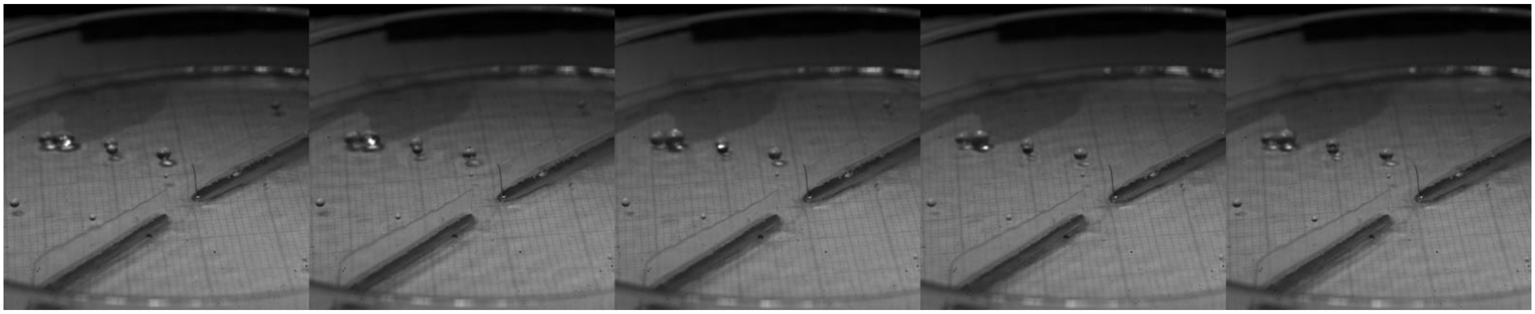
   iv. Able to observe Faraday instability regime at high speed as seen in Fig. 27.

g. Found out that during file saving, the camera must be connected to the computer.

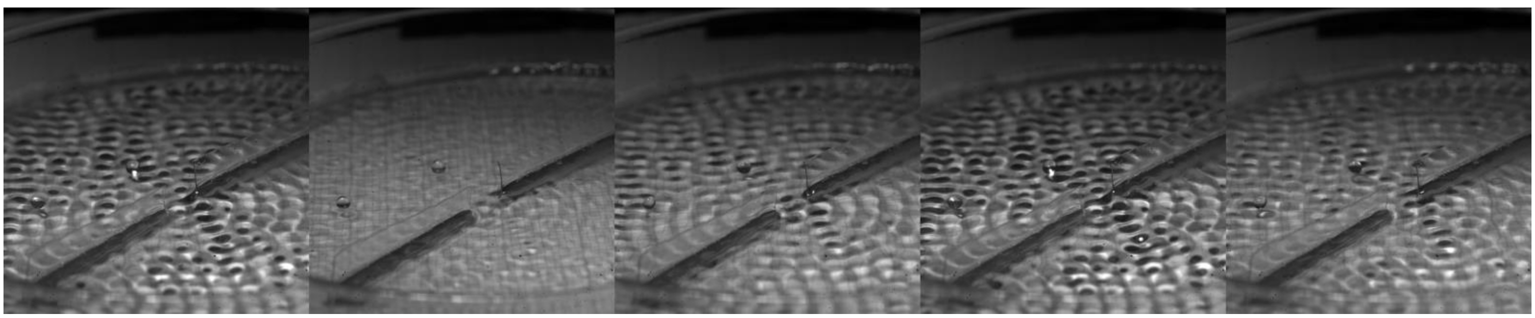
h. A self-improvised toothpick rotating mechanism can overcome the difficulty of producing consistent droplets and moving them towards the slits. Refer to improvements.



***25* Regular bouncing droplet captured at 1000 fps, the images here are 5 frames apart from each other, notice the ripples produced are much more enhanced and the vertical motion of the droplet can be seen clearly with the image on the far right being the point of highest bounce for the droplet**

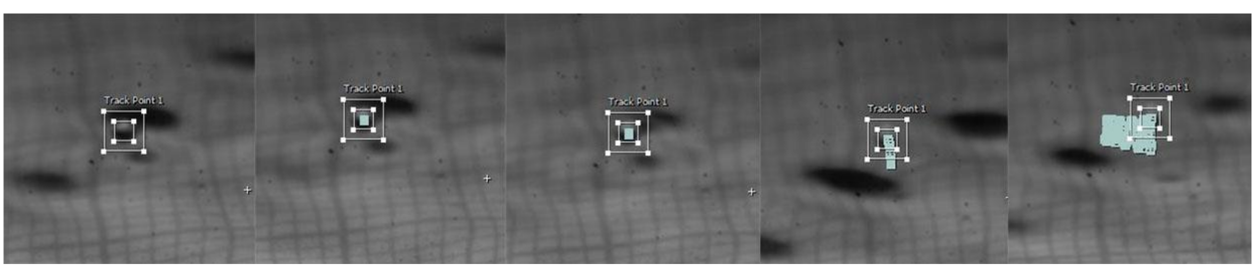


***26* Here multiple droplets were observed at once in ultra high speed, there are also two repelling droplets on the left hand side of the petri dish**



***27* Ultra high speed footage of droplets and the liquid interacting past the Faraday Regime**

16. Motion tracking of the high speed videos were carried out to observe the behavior of the droplet. This was carried out in Adobe After Effects where the tracking results are illustrated in Fig. 28 below:




Left to right

Fig. 28.1. Defining initial tracking point

Fig. 28.2. Tracking the first frame

Fig. 28.3. Tracking the first two frames

Fig. 28.4. Tracking of around 10 frames

Fig. 28.5. Results of tracking multiple bouncing periods

By applying the motion analysis to a null object created in After Effects, it creates a sequence of timeframes as shown in Fig. 29. The timeframes were copied into a text document and imported into Microsoft Excel.

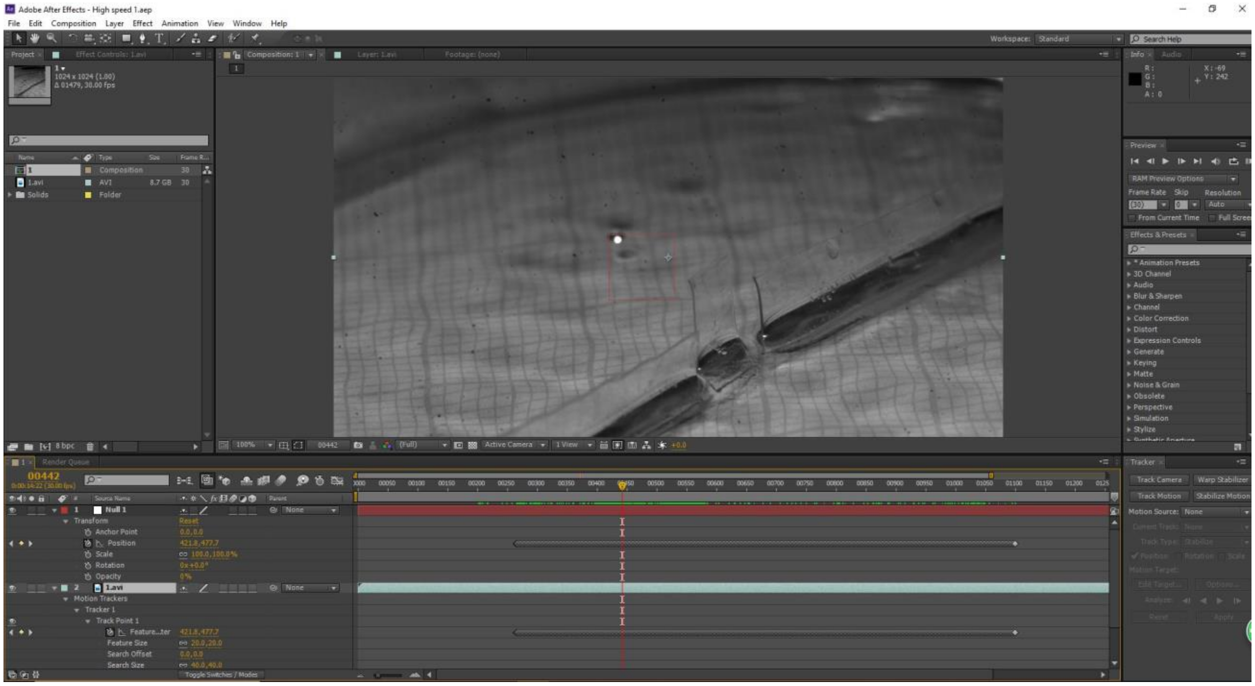



Fig. 29. Adobe After Effects motion tracking interface. It can be seen in the workspace that the tracking has produced a sequence of timeframes which records the coordinates of the tracked area. The null object was used as a data storage for timeframes.

The exported coordinates were of the format: frame, x coordinates, y coordinates. The coordinates were given in units of pixels. Since the video was recorded at 1000 fps, this means that each frame corresponds to 1 ms. The y coordinates were plot as a function of time as shown in Fig. 30. The choice of converting to time units is because of clearer representation of time scale of the bounces.

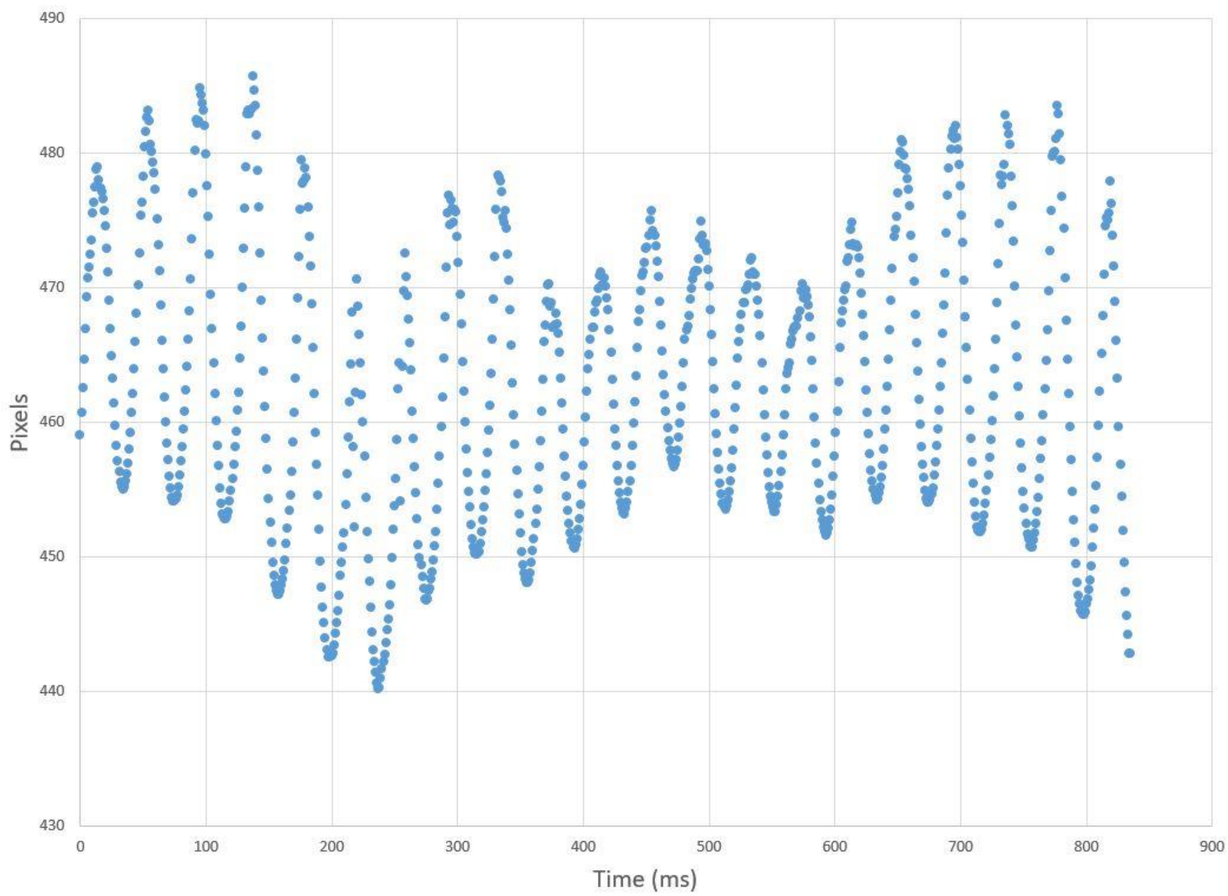



Fig. 30. Y coordinates of droplet motion as a function of time. This was recorded at a framerate of 1000 fps using a high speed camera.

Inferences can be drawn from this graph. First of all, the y coordinates do not strictly represent the height of each bounce. This is because the camera is not aligned with the surface of the liquid, but at an angle, due to limitations in focusing and capturing sufficient light. However the main contribution to the y coordinates is the change in height, so the graph clearly demonstrates an oscillatory motion of constant period. Difficulties in determining a quantitative measure of height is due to the y coordinates being a relative measure. A control needs to be set in order to quantify the y coordinates in units of length. For example, knowing the exact length of an object that is captured by the high speed camera. This allows a comparison between length and resolution.

A rough estimate of height could be carried out since the diameter of the petri dish was known. The plastic grating is somewhat centred on the diameter of the petri dish. Using Fig. 20, the centre of the petri dish can be estimated to be on the right edge of the centre grating. Drawing a straight line upwards to the edge of the petri dish gives an estimate of the radius which is known to be 2 " = 5.08 cm. The resolution of the video was known as it was set on the high speed camera to be 1024 by 1024. The distance to the edge was measured to be about 430 pixels. This means that the length conversion is 0.118 mm per pixel. Typical amplitudes from Fig. 30 are about the size of 15 pixels, which gives a height close to 1.8 mm. This is overestimated as the video was captured at angle of around 30 degrees as seen in Fig. 21. This stretches out the actual length which can be compensated by multiplying with the sine of the angle, which gives around 0.9 mm.

From Fig. 29 it can be seen that there is a bright dot at the bottom of the droplet. This was found during the review of the entire high speed video. At some of the bounces, it seems that a bright beam of light was produced. A frame by frame investigation of this phenomenon was conducted. This can be seen in Fig. 31 where a droplet completes a bounce.

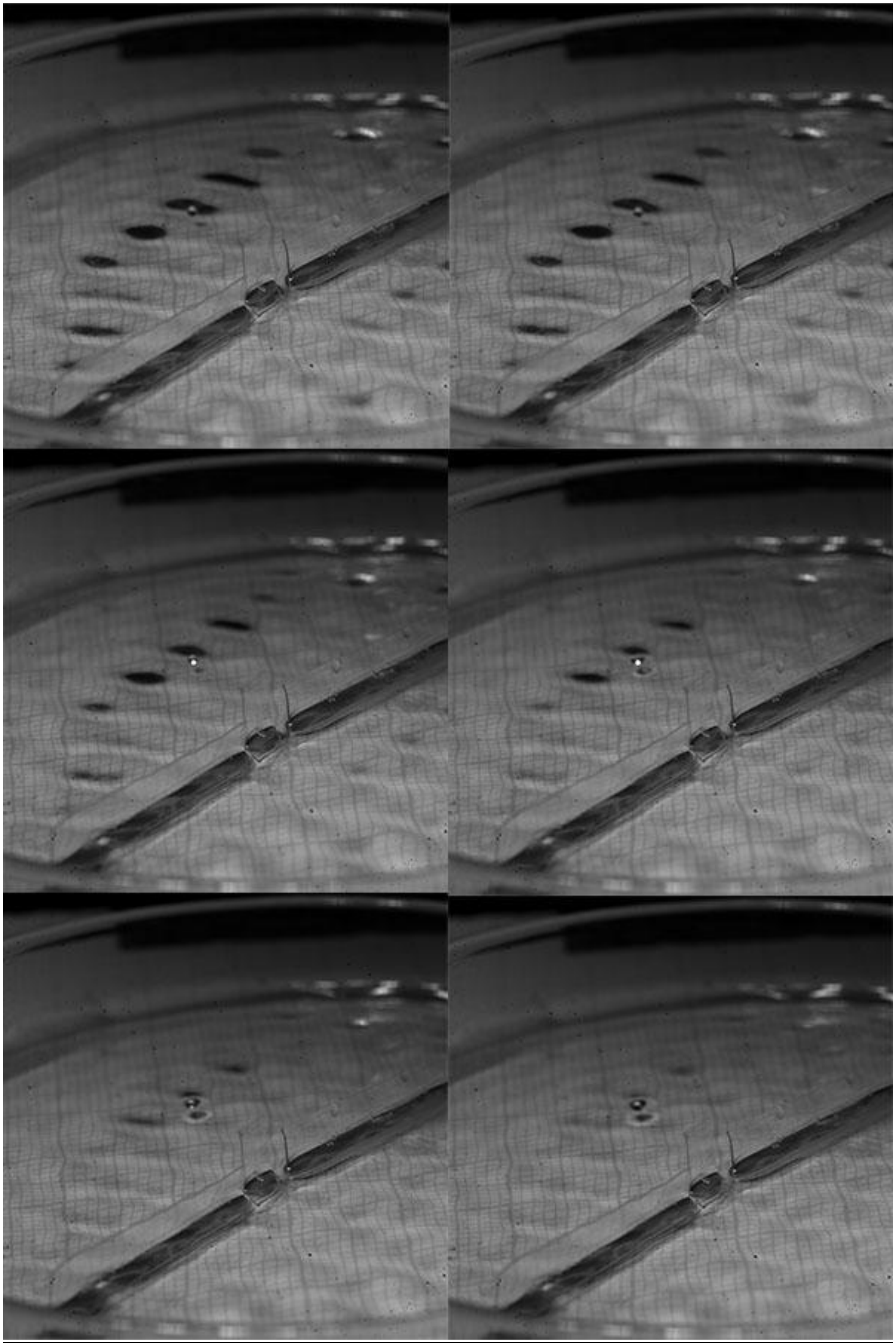


Fig.  31. Frame by frame capturing of the light beam phenomenon

This was an expected result. Close inspection of the high speed video gave interesting qualitative results. Certain bounces are actually two consecutive bounces with the first having a very small amplitude. Bounces that produces a beam of light are single bounces and seemed to propel to a greater amplitude. This suggests some sort of momentum conservation. Light beams also seem to occur in consecutive bounces. The droplet also seems to produce larger wave ripples as it hits the liquid surface. It is hypothesized that at certain oscillations, the droplet has built up enough potential energy to produce more energetic waves and even light. From Fig. 31, it also can be seen that the beam of light existed for longer than 1 ms since this is a frame by frame representation and the video was captured at 1000 fps. This means that it cannot be a single photon. A cascade of photon is required to capture a prolonged period and large cross section, which acts like a laser. There has been research conducted that suggested the possibility of droplets demonstrating atomic electron cloud density under Faraday regime.

Further investigation was done in trying to figure out the cause of horizontal motion under bouncing regime. This was not visible using the naked eye, which is why it remained unknown all along. A possible explanation is the use of the plywood plate and foldback clips. There could be random impulses due to the transmission process through the plate. The transmission of waves through a different material is much more complex to understand, which could have resulted in a modified driving force. The sinusoidal waveform could interact within the wood and superimpose to produce another waveform. This can also explain why the amplitude is not constant.

Essentially the horizontal impulse is due to the droplet colliding with the side of the bulge as explained in the theory section. The inclined surface can further complicate the propagation of light. The light intensity light was positioned such that it is almost normal to the surface of the liquid. A portion of it will transmit into the liquid, while others reflect on the surface. The transmitted intensity can further reflect off the bottom of the petri dish or transmit through. The bulge of the wave can act as a medium that focuses light and sends through a coherent beam under certain conditions.

Ongoing Improvements & Considerations

1. Paint the box and brand 'UCL'
2. Creating circular rings to secure the speaker, replacing the temporary wooden joints

Things we can try if we had more time

1. Rotating Fluid
    a. According to theory, if the entire set-up is rotated and droplets are provoked, these will eventually end up at the centre due to centripetal acceleration to the centre of the rotating body
    b. For two droplets which are 'repelling' this will create the illusory effect that they are orbiting each other
2. Observe Young's double slit interference pattern i.e. Quantum effects
    a. Via our bouncing droplet experiment, enough phenomena ('bouncing', 'walking', 'orbiting', surpassing of Faraday regime etc..) has been captured and observed to provide evidence for the Pilot-Wave theory which opposes the Copenhagen interpretation of quantum mechanics
    b. With this, double slit interference should be observable provided enough droplets travel through a 'barrier' as this is probabilistic. Attempting more of these with an ultra high speed camera for resolution and clarity would be ideal given a greater timeframe
        i. Interference patterns have been observed for a single droplet with the ultra high speed camera although this is it interacting with it's own waves reflected on the boundary of the petri dish
    c. There is also 'tunneling' which has been observed by another group *Insert reference* in which at the edge of the petri dish, there is a barrier and on the other side is a body of fluid also driven at the same frequency. Supposedly the droplet is able to 'tunnel' from one side of the barrier to another
3. Quantifying the droplet? Perhaps use more tracking technology as the droplet travels around the given space to get a better picture of the motion of the droplet by plotting the values on a graph or a heatmap of where the droplet traverses to on the petri dish to try and find any regular patterns of motion not yet known.
4. Method of producing consistent droplets

a. A common issue faced was producing droplets of consistent size, multiple mechanisms were thought of including a spring loaded pinpoint which would oscillate vertically and constantly dip into the fluid and create a droplet
b. Another one was a rotating mechanism (hand rotated) which had multiple pinpoints on the wheel of equal length. Once rotated each pinpoint would just prick the surface and create a droplet. This has the benefit of producing multiple droplets very rapidly and providing them with a horizontal momentum so could be used to push droplets towards any desired direction and may be beneficial to test something like a double slit experiment again where droplets need to travel through a barrier.