Motion in liquids

Research question: What is the relationship between the density of a liquid and the frequency of a mechanical wave generated in it by an external force? Measured with the Arduino Ultrasonic ranging module HC-SR04.

Physics Internal Assessment

hlk826 (002110-0028)

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Introduction

In topics 4.1 and 4.2 of the IB Physics Standard Level Curriculum the subjects of "Wave Oscillations" and "Traveling Waves" were covered by my class. During these intense sessions about waves and their behavior, I started wondering about the immense presence of waves in my everyday life.

The movement of pendulums and even the vibrations of the strings in a violin were a result of Simple Harmonic Motion (SHM), or a periodic motion with a fixed cyclical path, frequency, wavelength and a central equilibrium point. When a wave source executing SHM propagates energy without transferring matter to a medium, the initial oscillation then becomes a mechanical wave. Mechanical waves need direct contact with the medium to generate disturbance in its particles.

Thus, when an object is dropped into a liquid it will execute Simple Harmonic Motion and generate a mechanical wave in it. Exemplifying, when a person is stone skipping, the rock will create an oscillation in the water every time it bounces on it. At the final skip, the rock will exert an oscillation on the water and then it will sink. In this Internal Evaluation I wanted to find out if the amplitude and speed of the waves created in a liquid – by a same weight and at an equal distance – were related to its density. Finally, the following question emerges: **What is the relationship between the density of a liquid and the frequency of a mechanical wave generated in it by an external force?**

In order to understand how the waves in liquids are affected by the density of it, I investigated about the phenomenon of mechanical damping. According to Encyclopaedia Britannica (2020), damping is the "*restraining of vibratory motion*". It is the dissipation of energy that prevents or decreases vibration; it opposes the motion or force that is exerted on a system. This Internal Evaluation serves to demonstrate if the density of a liquid impacts directly in the resistance of it when an external force, like the dropping of a weight, creates oscillations in the liquid. Theoretically, *light damping* progressively decreases the amplitude of the waves in a liquid, meaning that the period and frequency are also affected by the phenomenon. While the period decreases, the frequency as inversely proportional will increase. In this experiment I expect to have the same effects over frequency when altering the density of eight liquids through the usage of water and liquid soap.

Also, to respond this inquiry, I combined it with my interest in programming. To find out the amplitude of the developed waves I will use the Arduino Ultrasonic ranging module HC-SR04. This ultrasonic sensor measures the time (in microseconds) that it takes a 40kHz sound to impact a surface and come back to the sensor. Therefore, if divided by the sound speed, the time the sensor imports to the Serial will indicate distance in meters. The sensor measures time in microseconds; thus, to use SI units I converted the *sound velocity in air* from meters per second to meters per microsecond:

$$340\,\frac{m}{s} = \left(\frac{1s}{1000000\mu s}\right) = 0.00034\,\frac{m}{\mu s}$$

The following equations will be used to determine the relationship between the density of a liquid and the oscillatory characteristics created on it:

$$\boldsymbol{T = \frac{1}{f}}$$

$$\boldsymbol{D = \frac{t'}{2} * 0.00034}\frac{m}{\mu s}$$

$$\boldsymbol{d = \frac{M}{v}}$$

$f = Frequency$
$T = Period$
$D = Displacement\ of\ the\ liquid$
$t' = Time\ in\ Serial$
$d = density$
$M = mass$
$V = volume$

Hypothesis

I consider that when a liquid is denser, it will generate waves with a larger amplitude and intensity. Therefore, its period, along with its velocity will also increase. Thus, when a liquid is denser, it will have a smaller frequency.

Variables

Independent variables: The density of each liquid measured in Kgm^{-3}. To measure the mass (kg), I will utilize a digital scale. For the volume of the liquids I will take the milliliters indicated in the 200ml beaker. The eight measured liquids will increase in density by 10% of concentration of liquid soap.

Dependent variables: The frequency of the waves generated in each liquid, measured in $s^{-1} or\ Hz$ calculated as the product in the division of one over the period in s. The period will be obtained through a subtraction of the x value at two coordinates where an oscillation of the wave is completed.

Controlled variables:

1. The metal mass that will be dropped into both liquids will remain constant at $0.50 \pm 0.01Kg$. Additionally, it will be attached to a string with negligible mass and force.
2. The height at which the weight is dropped will always be $0.16 \pm 0.01m$, this distance will be measured with a ruler, before dropping the weight.
3. The frequency of the sound that the Ultrasonic raging module HC-SR04 emits will remain at a constant 40kHz.

Materials

- Ultrasonic ranging module HC-SR04
- Arduino ELEGOO UNO3
- 4 Dupont wires
- 0.5kg weight
- 150ml of water
- 150ml of oil
- 10ml pipette

- Universal support
- 200ml Beaker
- Digital scale
- Metal ring

Method

Observation before beginning

1. To calculate the displacement of the wave in both liquids the Arduino Ultrasonic sensor should be programmed to indicate the time in μs that the sound emitted takes to bounce in the surface of the liquid and return to the sensor. For this it is necessary to have the correct wiring and module.
2. The Arduino Ultrasonic ranging module HC-SR04 has four entries. The sensor needs a pulse of 5 Volts for it to emit a sound of 40kHz. This 5 Volts will be provided by the Arduino ELEGOO UNO3, connecting the port of "5V" in the Arduino with the entry "Vcc" of the sensor.
3. The entry "Trig" indicates the Arduino when to send the sound wave, while the entry "Echo" receives the bouncing sound. The following image indicates the correct wiring of the Arduino and the sensor:

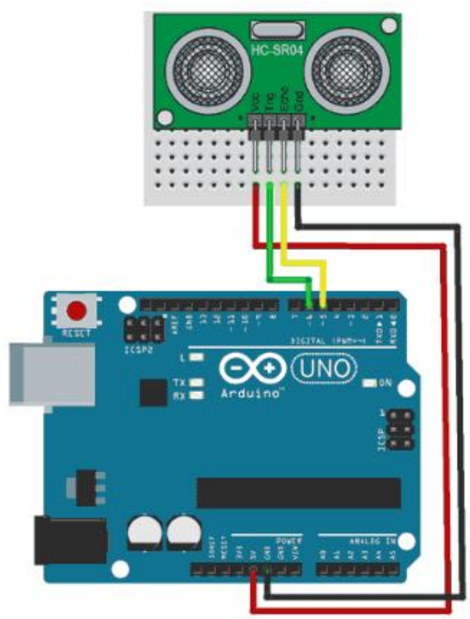

Image 1: Correct wiring for the Arduino and the Ultrasonic Raging Module. (Llamas, L., 2015)

4. Likewise, it is necessary to program the Arduino to print the time in μs in the "Serial" display and then convert it to meters using the equation stated above [Appendix 1].

5. The beaker and the liquid should be measured in the digital scale to know the liquid's mass before starting with the experiment.

Collection of Raw Data

6. To start with the collection of data it is necessary to position the 200ml beaker with the liquid below. With the help of a metal ring anchored to the universal support, one can place the Ultrasonic sensor above the beaker.
7. Then, the 0.5kg weight needs to be tied to the center of the metal ring, ensuring that it will be dropped right at the center of the beaker.
8. The Ultrasonic raging module can begin the measurements when the weight is positioned $0.16 \pm 0.01m$ away from the surface of the liquid. Ten measurements should be done throughout one second, so, each amplitude measure should correspond to $0.1 \pm 0.0005s$.
9. To modify the density of the liquid the concentration of liquid soap will progressively increase by ten percent in each liquid, staying with a same volume (200ml). To achieve an exact measurement of the milliliters of liquid soap that will be added to the water one can utilize a 10ml pipette. The first liquid used will have a 100% concentration of water.
10. Repeat the process with each of the eight liquids. Let the liquid settle in the beaker before dropping the weight on it.

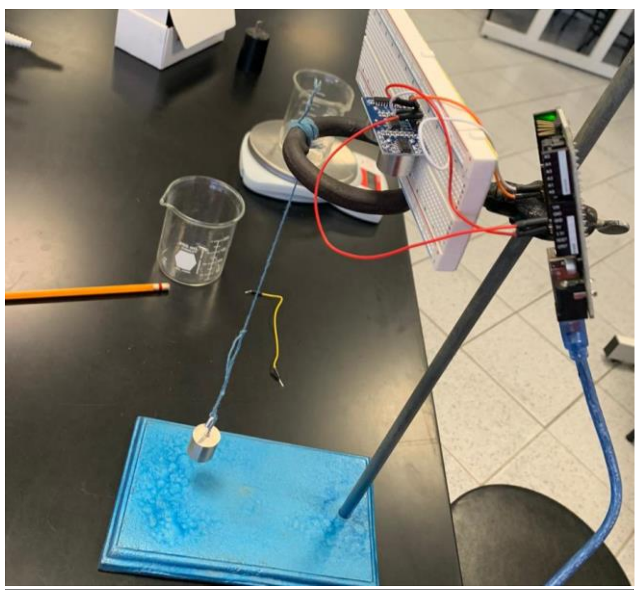

Image 2: Correct position of the metal ring, the Ultrasonic sensor and the weight

Analysis of Raw Data

11. The μs that were measured by the Ultrasonic sensor should be converted to meters using the following equation: $D = \frac{\boldsymbol{t\prime}}{\mathbf{2}} * \mathbf{0.00034}\frac{m}{\mu s}$
12. The time in seconds will be also indicated by the programmed measurements in the Serial display of the Arduino.

13. With the help of the Windows program "Logger Pro", the amplitude of the oscillations in meters can be plotted over the time in seconds that it took to measure the distance between the liquid and the sensor. The "best fit" cosine equation can be found with the programs' function of: "Curve Adjust"; hence, the period of the waves can be obtained by subtracting the x values of two coordinates, belonging to points where an oscillation is completed.
14. Afterwards, the frequency will be given by the equation: $\boldsymbol{T = \frac{1}{f}}$, the uncertainties will be calculated by adding the absolute uncertainties of both points in the graph and given their percentage uncertainty, the absolute uncertainty of the frequency can be measured.
15. Finally, by plotting the density of each liquid against its obtained frequency one can identify if there is a direct proportional relationship between the both variables. If this relationship is confirmed, the increasing or decreasing rate will be stated.

Risk assessment

This experiment does not pose great physical risks; although, the 0.5Kg weight needs to be dropped carefully to the beaker, ensuring that it will fall in the liquid, to not break the 200ml beaker. The experiment has few to no ethical and environmental consequences.

Raw Data

<u>Density of each liquid</u>

As stated before, the density of the liquids will be modified by increasing the percentage of the concentration of liquid soap in the 200ml. In the following table the mass and the volume of each liquid was recorded, with both of these quantities the density of the eight liquids was measured.

Liquid	*Water Concentration*	*Liquid Soap Concentration*	*Mass* (kg)	*Volume* (m^3)	*Density* (kgm^{-3})	ΔM (kg)	ΔV $(x10^3 m^3)$	$\Delta M/M$ %	$\Delta V/V$ %	Δd (kgm^{-3})
1	100%	0%	0.19400	0.00020	970.00	0.00001	0.00050	0.00515	0.25000	2.4750
2	90%	10%	0.19440	0.00020	972.00	0.00001	0.00050	0.00514	0.25000	2.4800
3	80%	20%	0.19690	0.00020	984.50	0.00001	0.00050	0.00508	0.25000	2.5113
4	70%	30%	0.19948	0.00020	997.40	0.00001	0.00050	0.00501	0.25000	2.5435
5	60%	40%	0.20202	0.00020	1010.10	0.00001	0.00050	0.00495	0.25000	2.5753
6	50%	50%	0.20456	0.00020	1022.80	0.00001	0.00050	0.00489	0.25000	2.6070
7	40%	60%	0.20710	0.00020	1035.50	0.00001	0.00050	0.00483	0.25000	2.6388
8	30%	70%	0.20960	0.00020	1048.00	0.00001	0.00050	0.00477	0.25000	2.6700

Table 1: Densities calculated for 8 liquids with different concentrations of liquid soap, with uncertainties.

Frequencies

To obtain the amplitudes of the oscillations created in each liquid I converted the output of the Arduino Ultrasonic module in microseconds [Appendix 1] to meters using the equation stated in the *Analysis of Raw Data*. Then, when these values where plotted against time in seconds, I utilized two coordinates to obtain the period of the wave (T). Finally, with the period I utilized the equation of inverse relationship between period and frequency to calculate the frequency (f) of the waves created by an external force of $0.50 \pm 0.01Kg$ in the eight different liquids. For Liquid 1 and Liquid 2 I presented all the calculations and formulas to obtain the frequency. On the other hand, the remaining six frequencies, along with their absolute uncertainties, where gathered in [Table 4].

Liquid 1

t(s)	*t′ (μs)*	*D(m)*	*Δt (s)*	*Δt/t (%)*	*ΔD (m)*	*ΔD/D (%)*
0.00	1657	0.31483	0.0005	0.0000	0.00001	0.00318
0.10	1943	0.36917	0.0005	0.5000	0.00001	0.00271
0.20	1599	0.30381	0.0005	0.2500	0.00001	0.00329
0.30	1887	0.35853	0.0005	0.1667	0.00001	0.00279
0.40	1674	0.31806	0.0005	0.1250	0.00001	0.00314
0.50	1843	0.35017	0.0005	0.1000	0.00001	0.00286
0.60	1702	0.32338	0.0005	0.0833	0.00001	0.00309
0.70	1826	0.34694	0.0005	0.0714	0.00001	0.00288
0.80	1713	0.32547	0.0005	0.0625	0.00001	0.00307
0.90	1796	0.34124	0.0005	0.0556	0.00001	0.00293
1.00	1728	0.32832	0.0005	0.0500	0.00001	0.00305

Table 2: Time and displacement of the waves created in Liquid 1 by a 0.5kg weight.

Data Analysis

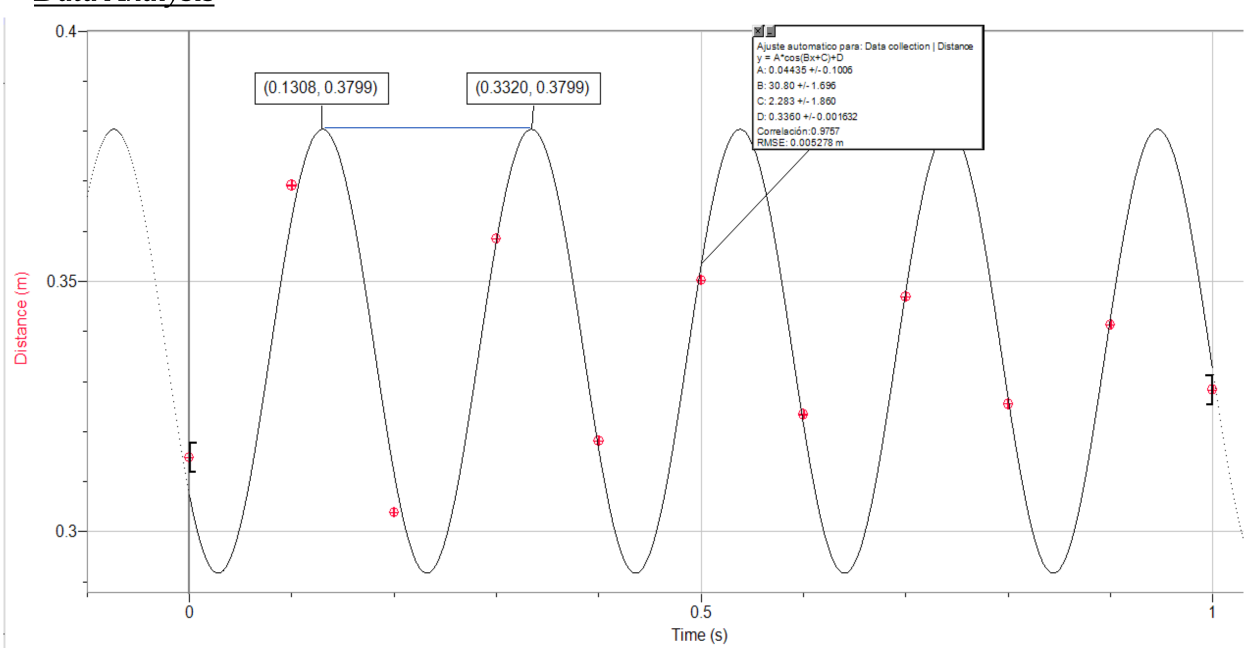

Image 3: Displacement plotted over time in a cosine best fit equation for Liquid 1 oscillations.

Period and frequency of Liquid 1 oscillations

$$T = (0.3320s \pm 0.0005) - (0.1308s \pm 0.0005)$$
$$T = 0.2012 \pm 0.001s$$

$$\frac{\Delta T}{T} = \frac{0.001 * 100}{0.2012}, \quad \frac{\Delta T}{T} = \frac{0.001 * 100}{0.2012}, \quad \frac{\Delta T}{T} = 0.49\%$$

$$\boldsymbol{T = \frac{1}{f}} \qquad \boldsymbol{f = \frac{1}{T}}$$

$$f = \frac{1}{0.2012 \pm 0.001s}, \quad f = 4.970Hz$$

$$\Delta f = \frac{4.979 * 0.49}{100s}, \quad \Delta f = 0.0244$$

$$f = 4.970 \pm 0.0244Hz$$

Liquid 2

t(s)	*t' (µs)*	*D(m)*	*Δt (s)*	*Δt/t (%)*	*ΔD (m)*	*ΔD/D (%)*
0.000	1693	0.32167	0.0005	0.0000	0.00001	0.00311
0.100	1971	0.37449	0.0005	0.5000	0.00001	0.00267
0.200	1672	0.31768	0.0005	0.2500	0.00001	0.00315
0.300	1902	0.36138	0.0005	0.1667	0.00001	0.00277
0.400	1716	0.32604	0.0005	0.1250	0.00001	0.00307
0.500	1872	0.35568	0.0005	0.1000	0.00001	0.00281
0.600	1767	0.33573	0.0005	0.0833	0.00001	0.00298
0.700	1833	0.34827	0.0005	0.0714	0.00001	0.00287
0.800	1796	0.34124	0.0005	0.0625	0.00001	0.00293
0.900	1824	0.34656	0.0005	0.0556	0.00001	0.00289
1.000	1815	0.34485	0.0005	0.0500	0.00001	0.00290

Table 3: Time and displacement of the waves created in Liquid 2 by a 0.5kg weight.

Data Analysis

Period and frequency of Liquid 2 oscillations

$$T = (0.3358s \pm 0.0005) - (0.1332s \pm 0.0005)$$
$$T = 0.2026 \pm 0.001s$$

$$\frac{\Delta T}{T} = \frac{0.001 * 100}{0.2026}, \quad \frac{\Delta T}{T} = \frac{0.001 * 100}{0.2026}, \quad \frac{\Delta T}{T} = 0.49\%$$

$$f = \frac{1}{0.2026 \pm 0.001s}, \quad f = 4.936Hz$$

$$\Delta f = \frac{4.979 * 0.49}{100s}, \qquad \Delta f = 0.0245$$

$$f = 4.936 \pm 0.0245Hz$$

Density and Frequency relationship

$Liquid$	$Density$ (kgm^{-3})	$Frequency$ (Hz)	Δd (kgm^{-3})	Δf (Hz)
1	970.00	4.9700	2.4750	0.0244
2	972.00	4.9360	2.4800	0.0245
3	984.50	4.9110	2.5113	0.0240
4	997.40	4.8900	2.5435	0.0238
5	1010.10	4.8420	2.5753	0.0234
6	1022.80	4.7980	2.6070	0.0229
7	1035.50	4.7520	2.6388	0.0223
8	1048.00	4.7100	2.6700	0.0221

Table 4: Gathered measures of density and frequency for the eight liquids with their respective absolute uncertainties.

Plotted data

The gathered densities (kgm^{-3}) and frequencies (Hz) were plotted in "Logger Pro" along with their absolute uncertainties; with the function of "Linear Fit" I could identify the slope or the decreasing relationship between both variables. Additionally, to calculate the absolute uncertainty (Δr) of the decreasing rate, I plotted the maximum and the minimum lines, according to the error lines of the first and last liquid values.

There is not a directly proportional relationship, because the plotted line does not passes through zero. Although, there is an inversely proportional relationship between the density and the frequency of the liquids. Meaning that as the density increases, the frequency of the oscillations created in the liquid by an external object decreases.

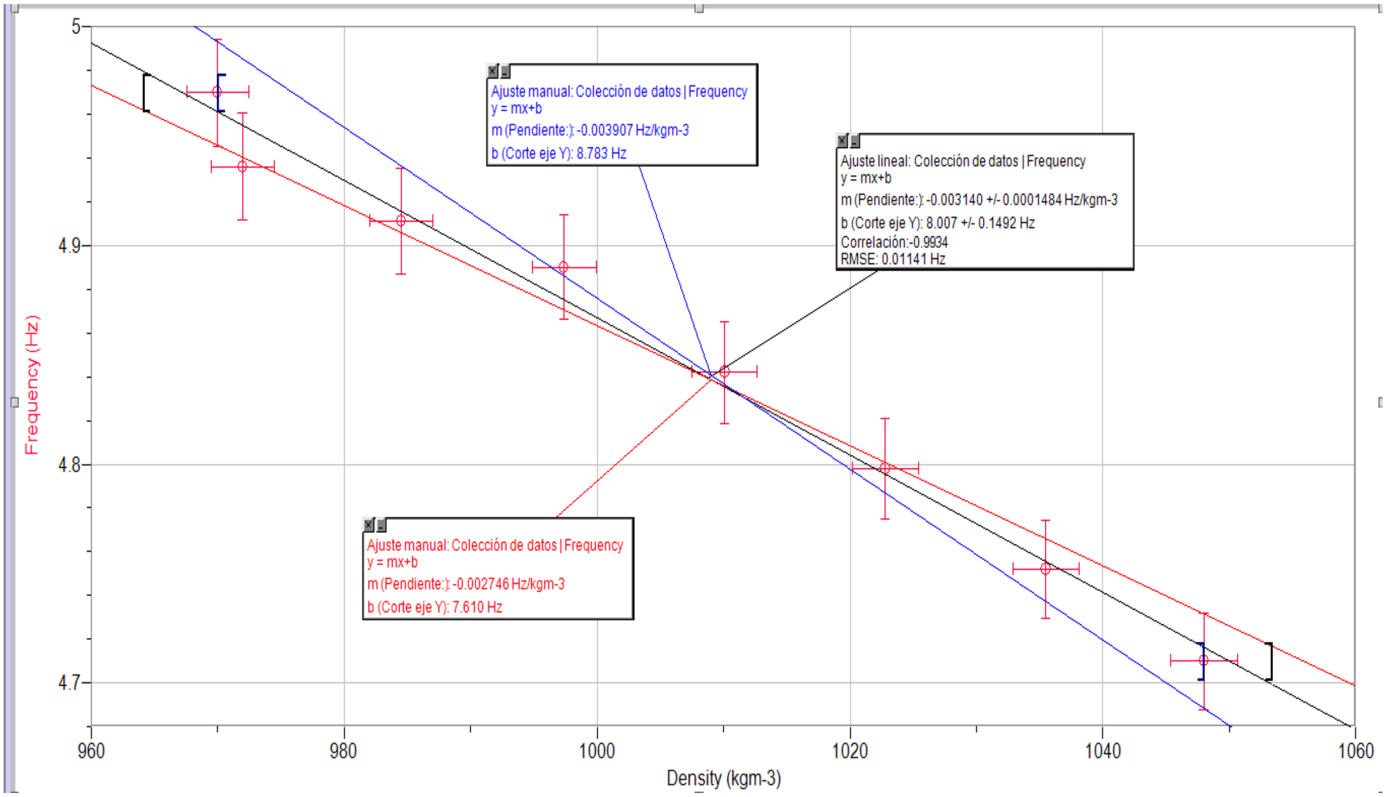

Image 4: Frequency plotted over density in a linear fit equation for the eight liquids.

The decreasing rate between density and frequency (r) is: $-0.00314kgsm^3$

$$\Delta r = \frac{MAX - MIN}{2}, \qquad \Delta r = \frac{-0.00391 + 0.00275}{2}, \qquad \Delta r = -0.00058$$

Thus, $r = -0.00314 \pm -0.00058kgsm^3$

Conclusion

This experiment was made to find out if the density (kgm^{-3}) of a liquid directly affected the frequencies (Hz) of the waves created on it by an external force. Measuring the amplitude of the waves created with the Arduino Ultrasonic ranging module HC-SR04. Analyzing the data and graphs obtained in this Internal Evaluation it can be confirmed that the results partially agreed with the proposed hypothesis.

It is true that the less dense medium had the greatest frequency and the lesser period. Meaning that the oscillations propagated more rapidly in Liquid 1, thus, as frequency is inversely proportional to the period, the value of it was greater in a concentration of 100% percent water. These values worked accordingly with the background information about damping, which states that the amplitude and period of the oscillations of the waves will decrease based on the vibration resistivity of the system. Thus, density affects directly the period and frequency of the waves created on the liquids by the drop of a 0.50±0.01Kg weight.

Finally, the question regarding this Internal assessment: “What is the relationship between the density of a liquid and the frequency of a mechanical wave generated in it by an external force?” is answered with [Image 4] where the plotted values of frequency against density are shown, both values share an inversely proportional relationship, but not a directly proportional relationship. This conforms to the inverse proportionality of frequency and period, which was stated in the introduction and procedures on the *Analysis of Raw Data*. The decreasing rate of change between density and frequency was calculated and as expected, it was negative, conforming to the proportionality stated above.

Evaluation

Further research

The results of this experiment can be applied to a real-life situation in the creation and utilization of buoys, which function with transversal waves in the ocean. Buoys usually guide boats and indicate the tide of the ocean. The movement of this buoys can be affected by the concentration of salt in water, therefore, the density of the ocean they are in. Hence, it is necessary to consider the damping that affects the buoys when they are in different water systems.

Weaknesses and strengths

This experiment was moderately accurate, the quantities that I measured were minuscule, meaning that every random or systematic error committed would have impacted greatly the experiment. Additionally, the experiment was executed on a school lab, without high-end materials, which could have altered the results in the experiment.

Systematic errors

- Error in the calibration of the Arduino Ultrasonic ranging module HC-SR04 with each liquid.

  As I did not fixate the Ultrasonic Sensor to the metal ring it suffered various movements that affected its calibration and the measurements in microseconds that the emitted sound outputted. This error can be appreciated in [Table 2] and [Table 3], their measurement in 0 seconds should remain the same, because the volume is conserved. Although, it is different in every liquid measurement.

  The improvement for this error could be the usage of scotch tape to fixate the sensor to the metal ring. Additionally, to keep the volume of the liquids as exact as possible, one could use a professional pipette or a pipette with a lesser capacity of milliliters.

- Uncertainties of the sound emitted by the Arduino Ultrasonic ranging module HC-SR04 not considered.

  The Ultrasonic Sensor is not a professional sensor, it must be programmed by an individual; therefore, its measurements have an uncertainty of approximately $\pm 0.003m$. Meaning that most of the measurements could have been affected by a systematic error. I do not recommend working with an Arduino sensor when measuring minuscule changes. This error can be appreciated in [Image 4], where some of the calculated values have a greater distance to the plotted line.

An improvement for this error could be using another type of sensor to measure the amplitude of the waves generated in the liquids by an external force. For example, a reliable sensor that could be used is the Logger Pro Motion Detector.

Random errors

- Different distances from which the weight was dropped.

  As I did this experiment alone it was almost impossible to calculate the exact distance from where I needed to drop the 0.5kg mass. It is probable that the distances changed throughout the experiment. This error can be appreciated in the number of frequency values; originally, I had ten liquid densities calculated, but the frequencies in two of the liquids did not match the plotted line in [Image 4], so I decided to remove the values from the experiment.

  The improvement that I suggest is having an exact mark or ruler alongside the universal support, so one can identify where should the weight be dropped. Other solution is asking for help to another person, so the distance is measured in every drop.

Strengths

- Arduino Ultrasonic measuring every 0.1 seconds.

  Taking the measurement of displacement in a reduced time allows one to exactly capture the oscillations of the waves created in the liquid every 0.1 seconds, thus, reducing the systematic errors affecting the measurement of time in microseconds that the sound takes to impact the surface of the liquid and to return to the module. These values were recorded in [Table 2] and [Table 3].

- Using a same volume for each liquid.

  Using a same volume allowed me to monitor the density of each liquid correctly. Additionally, by using a same volume I could use the same beaker multiple times, hence, I did not alter the ignored mass of the experiment; reducing the random errors present in the calculation of the density for each of the eight liquids.

Appendixes

```
Programa_Arduino_Sensor
#define EchoP 11
#define TrigP 12
long tiempo, distancia;

void setup() {
  Serial.begin (9600);
  pinMode (EchoP, INPUT);
  pinMode (TrigP, OUTPUT);
}

void loop() {
  digitalWrite(TrigP, LOW);
  delayMicroseconds (2);
  digitalWrite(TrigP, HIGH);
  delayMicroseconds(10);
  digitalWrite(TrigP, LOW);

  tiempo=pulseIn(EchoP, HIGH);
  distancia=((tiempo/2)*0.00034);

  if(distancia >=500){
    Serial.println("error");
  }
  else{
    Serial.print(distancia);
    Serial.println("m");
    Serial.print(tiempo);
    Serial.println("micro seconds");
    digitalWrite(4,0);
```

Appendix 1: Code used for the Arduino, for it to output the time in microseconds that the Arduino Ultrasonic raging module measured from the metal ring to the surface of the various liquids.

References

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