FIA 2020/22
XII CONGRESSO/CONGRESO IBEROAMERICANO DE ACÚSTICA
XXIX ENCONTRO DA SOCIEDADE BRASILEIRA DE ACÚSTICA - SOBRAC
Florianópolis, SC, Brasil

# Glass bottles as wind musical instruments: An experimental method to predict the pitch based on the volume of water inside the bottle

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## Abstract

The phenomenon of blowing on the neck of glass bottles and producing sound is very familiar to the general public. In fact, they can be treated as a professional set of wind musical instruments, as the musical group *The Bottle Boys* (http://thebottleboys.com/) do. With a certain collection of bottles, different tones can be obtained by varying the bottle shape, or the volume of water inside them, in a way that the pitch is higher as the volume of water increases. In this context, this work presents an experimental method to predict the volume of water necessary to get a specific musical note from blowing up at the neck of any general glass bottle, based on the fact that glass bottles behave like Helmholtz resonators. The method was applied using the free Android cell phone app *Spectroid* to measure the frequency of the sound produced by blowing the bottle, and also a graduated cylinder to measure the volumes of water, but common materials such as kitchen graduated cups can be used also. With this experimental setup, an experiment is done measuring the frequency of the sound produced by the glass bottle, relating it with its corresponding volume of water. After data acquisition, the Helmholtz resonator equation is applied to fit the data, and a characteristic curve of the bottle is established. With this result it is possible to predict how much volume is necessary to be insert in the bottle to obtain a desired musical note. Experimental errors are taking into account, three different types of bottles were analyzed to verify the validity of the method along with a commercial chromatic tuner by *Korg*, and tables relating the pitch and its corresponding volume of water for each bottle studied were produced from application of the method.

**Keywords:** Acoustics, Glass bottle, Helmholtz Resonator, Tuning, Physics.

**PACS:** 43.75.Qr, 43.75.Yy, 43.66.Hg, 43.58.Kr, 43.75.-z.

## 1. INTRODUCTION

Musicians around the world use glass bottles as musical instruments by blowing at the neck of the bottle (Figure 1), producing one single tone sound.

**Figure 1:** Mouth positioning to blow on the neck of a glass bottle and produce sound.

The international music group *The Bottle Boys* (http://thebottleboys.com/) is one of the best examples of the use of bottles as wind instruments. Each musician holds an ensemble of bottles with different shapes, as well as the amount of water inside them. With that, blowing the right bottle at the right time produce the musical note that is supposed to be played at this very moment. This ensemble of bottles constitutes a wind musical instrument rich on notes and possibilities to play different songs.

As musical instruments, glass bottles need to be tuned, and it is important for musician to know how to tune them. A guitar tuner cell phone app can be used to do so, in order to achieve a specific pitch. The musician may blow at the neck of the bottle while measures the tone with the smartphone app, and if the pitch is too low for example, water volume can be enhanced to increase pitch. The bottle size and geometry affects the possible tones for a given bottle. Thus, different bottles can be used to achieve different tones, and each bottle could receive a certain amount of water. This method of tuning is very practical and accessible, but the physics behind glass bottles can help musicians to predict approximately how much water is necessary for a specific tone. The presented paper proposes a method that may be used to study glass bottles and predict this filler volume. That may represent a shortcut to get the amount of water needed to tune bottles.

## 2. FUNDAMENTALS

The physics of glass bottle blowing, in first approximation, is the same physics of the Helmholtz resonator. Authors from [1–5], for example, define the Helmholtz resonator as a rigid-walled cavity of volume $V$, with an opening end to air through a neck[1] of length $l$ and area $A$ as illustrated on Figure 2a.

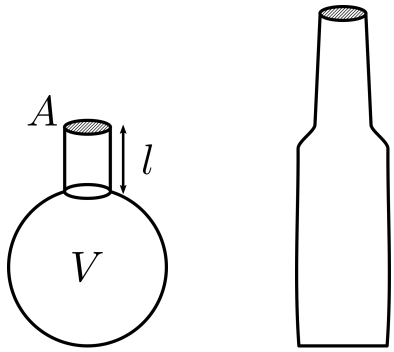


**Figure 2:** (a) Ideal Helmholtz resonator with spherical cavity and cylindrical neck. Its volume $V$, area of the opening $A$ and length of the neck $l$ are well defined by its geometry. (b) Glass bottle. Despite its geometry, it could be still considered as a Helmholtz resonator.

As a consequence of its complicated design and variety, glass bottles do not have well defined geometry and dimensions. One cannot easily approximate a given commercial beer bottle, for example, to a spherical-cylindrical shaped resonator, this kind of assumption would represent a strong approximation. However, these types of bottles still fit in the definition of a Helmholtz resonator, because they are enough rigid to be considered as rigid-walled cavity endowed with a neck opened to the air.

Therefore, the main hypothesis of this work is

[1] Helmholtz resonators actually don't need to have a neck, as shown in [3] pg. 108, Fig. 5-2a. See the last paragraph of [3], chapter 5, section 9 for a discussion about that.

that sound produced frequency by glass bottles can be described by the Helmholtz resonator equation [2]:

$$f = \frac{c}{2\pi}\sqrt{\frac{A}{Vl}} \tag{1}$$

Where $f$ is the natural frequency of the resonator, $c$ is the speed of sound in the air, $A$ is the area of the neck's end, $V$ is the resonator cavity volume, and $l$ is the neck length (See Figure 2a).

If the quantities in equation (1) are constant, except the volume, the dependence between frequency and volume can be written as in (2):

$$f = k\sqrt{\frac{1}{V}} \tag{2}$$

Where $k$ is defined by (3):

$$k = \frac{c}{2\pi}\sqrt{\frac{A}{l}} \tag{3}$$

Equation (2) is particularly interesting to study glass bottles, because when a bottle is tuned to a specific musical note, water inside adjusts only the effective cavity volume $V$, that is smaller than the original volume $V_0$ (See Figure 3).

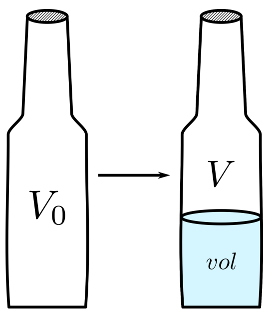


**Figure 3:** A glass bottle without water has a volume of cavity $V_0$. However, when water is put inside it, the actual volume $V$ is its original volume $V_0$ minus the added water volume $vol$.

The last statement takes into account the hypothesis that water inside the bottle behaves like a new rigid bottom, because of water low compressibility compared to air.

Writing these considerations on equation form – volume $V$ becomes $(V_0 - vol)$ – which leads to:

$$f = k\sqrt{\frac{1}{(V_0 - vol)}} \implies \tag{4}$$

$$f^2 = \frac{k^2}{(V_0 - vol)} \therefore \tag{5}$$

$$vol(f) = V_0 - \frac{k^2}{f^2} \tag{6}$$

The result on equation (6) shows explicitly that the water volume $vol$ depends on the produced frequency $f$, and bottle geometry, represented by parameters $V_0$ and $k$. To find these parameters, a set of experimental values of $f$ and $vol$ can be fitted by equation (6), which makes this equation useful for predicting the volume $vol$ necessary to produce a given musical note with frequency $f$.

## 3. DEVELOPMENT

### 3.1 The Method

The experimental method developed on this work starts with measuring the frequency of sound produced by blowing on the neck of an empty general bottle (testing bottle), no particular bottle is required. The first frequency, measured with the android smartphone app *Spectroid*, corresponds to $vol$ equals zero or an empty bottle. As a second step, different known volumes of water (testing volumes) are pouring into the bottle, generating different frequencies that can be measured one by one, creating a table of $f$ versus $vol$.

Each testing bottle will determine a range of volumes, ex: a 275 mL bottle can be studied from 0 mL up to 250 mL for example. The limit of 250 mL is imposed by the fact that the water level on the bottle must be lower than the neck base. Precision bottle fill up is achieved using an auxiliary reservoir (for example item (b) and (c) from Figure 5) and a pipette (item (d) of Figure 5). Be-

[2]The German physicist Herman L. F. Helmholtz developed this equation and also one of the first studies about the sensations of tone by the human ear (See [6]).

fore water level gets near to desired volume, the pipette could be used to finish the proper filling process. The graduated cylinder allows a clear measuring of *vol* that will be transferred to the bottle.

This volume versus frequency calibration process, for a given bottle, stops when this very bottle is almost filled with water, at that level sound is very difficult to be produced[3].

After data acquisition, the numerical fitting process starts by putting the data into a Python script using the software *Spyder* that adjust the parameters $V_0$ and $k$ of equation (6) with respect to experimental data by the method presented in section 6.5 of [7]. The adjusted parameters can be used to calculate the volume of water necessary to produce a sound of frequency $f$.

Helmholtz resonator once blown for any volume will result in harmonic oscillation of frequency $f$, it is not true that this given frequency will be a musical tone. Musical scales are an ensemble of discrete well established notes, where $f$ must be always respect. The calibration process described before do not supposes any compromise with any musical scale. So, one can say that the proposed method is a general way to tune a generic bottle as a generic Helmholtz resonator.

### 3.2 Materials

The study presented here used three commercial bottles (Figure 4) as test and example of the proposed method. The water measurements were done with the devices presented in Figure 5, the sound frequency produced by the bottles was measured by a smartphone and became numerical inputs of the method. A commercial guitar tuner was used in the method validation process (See Figure 6).

[3]Blowing into the neck of an almost full bottle may demand an appreciable blow force. It is recommended to do the bottle calibration procedure carefully, interleaving breaks between blowing in order to avoid dizziness and fatigue

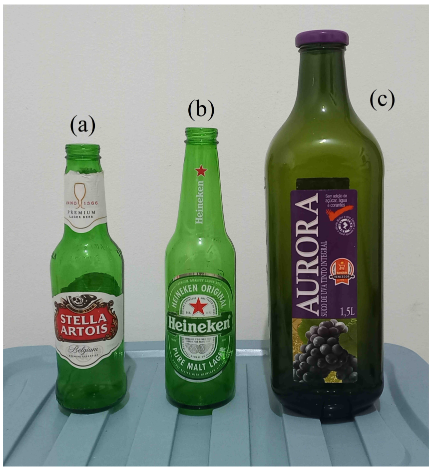


**Figure 4:** Bottles studied: (a) 275 mL Stella Artois beer bottle. (b) 330 mL Heineken beer bottle. (c) 1500 mL Aurora grape juice bottle.

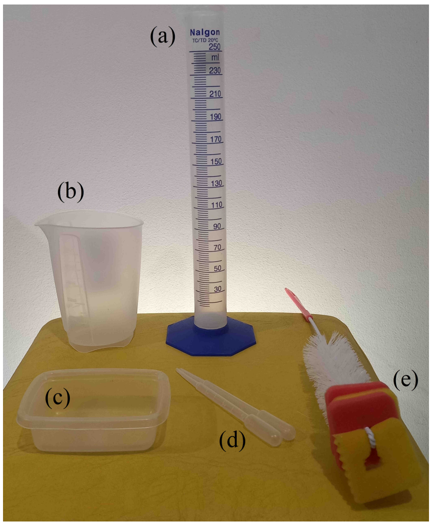


**Figure 5:** Measuring devices used in water volume determination: (a) 250 mL Nalgon plastic graduated cylinder. (b) 500 mL Sanremo plastic measuring cup. (c) Plastic container. (d) 3 mL plastic pipettes. (e) Bottle brush.

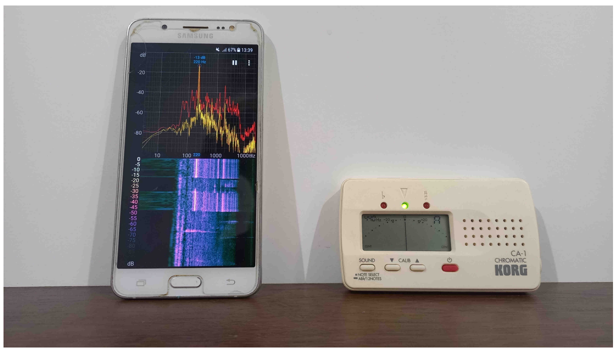


**Figure 6:** Frequency measuring equipment: Samsung Galaxy J5 Metal smartphone with the app *Spectroid* running, and CA-1 *Korg* Chromatic Tuner.

### 3.3 Experimental errors treatment

In order to start the experimental procedure that will result on the data-set used as input of the method discussed on this paper, the sound frequency produced by the person blowing on a bottle neck must be measured on a comfortable position regarding the person. The tone obtained could be not univocal, it means that a slightly different position of blowing can generate a quite different tone. Indeed, the position of human mouth blowing on bottle necks affects the sound produced, what can impact experimental errors on the resonance frequencies determination.

This experimental uncertainty is expected, because resonance phenomena occurs as a bell shaped curve, with certain half width (See [8] pg. 108 for a discussion about this concept). Talking about sound resonances, what one call resonance frequency is the central frequency at resonance curve the peak. Fact that not avoid near frequencies, side by side central frequency, to appear reinforced as well. A way to deal with that, can be solved using the instrument possibilities: while the *Spectroid* app is running on the smartphone, the person may change his mouth position to get a minimum frequency (named $f_-$) and a maximum frequency ($f_+$). It should be take into account that this interval between $f_-$ and $f_+$ ($\Delta f_{mouth}$) is obtained by a completely experimental approach, no rule determine this interval, that may be a result of the operator sensitivity and feeling.

It is well-known that the app Spectroid has its own uncertainty $\Delta f_{Spectroid}$ but the uncertainty $\Delta f_{mouth}$ due to the mouth position showed to be dominant. Thus, the absolute error associated to the resonance frequency, or the central frequency, is a half of $\Delta f_{mouth}$ (the difference between the maximum and the minimum frequency of the resonance). This error was named $\Delta f$ and its mean value $\overline{\Delta f}$ was taken as the general error associated to a given bottle, as defined in equation (7):

$$\overline{\Delta f} \equiv mean\left(\frac{f_+ - f_-}{2}\right) = mean(\Delta f) \tag{7}$$

Once the error $\Delta f$ is defined, the water volume error can be calculated as a propagation of $\Delta f$. In first approximation, as presented in the equation (8.2) of [9], the error $\Delta vol$ due to an error $\Delta f$ is calculated as:

$$\Delta vol = \left|\frac{\mathrm{d}vol}{\mathrm{d}f}\right| \Delta f \tag{8}$$

Considering now that $vol$ is given by equation (6), with $V_0$ and $k$ as constants, equation (8) becomes:

$$\Delta vol = \left|\frac{\mathrm{d}}{\mathrm{d}f}\left(V_0 - \frac{k^2}{f^2}\right)\right| \Delta f \implies \tag{9}$$

$$\Delta vol = \left|k^2 \frac{\mathrm{d}}{\mathrm{d}f}\left(-\frac{1}{f^2}\right)\right| \Delta f \implies \tag{10}$$

$$\Delta vol = \left|k^2 \left(\frac{2}{f^3}\right)\right| \Delta f \therefore \tag{11}$$

$$\Delta vol = \left(\frac{2k^2}{f^3}\right) \Delta f \tag{12}$$

The previous result (12) implies that for each $\Delta f$ obtained from the experimental data-set a value of $\Delta vol$ is determined. For simplicity, as assumed on frequency error determination, mean value of $\Delta vol$ can be calculated and taken as a good guess for the uncertainty on the required water volume for a given tone. The tolerance on water volume prediction and the error bars showed during method validation section correspond exactly to the values of $\overline{\Delta f}$ and $\overline{\Delta vol}$.

## 4. RESULTS AND DISCUSSIONS

Experimental data obtained studying the three glass bottles (Stella Artois beer, Heineken beer, and Aurora grape juice) are presented on Tables [1, 2 and 3].

**Table 1:** Measurement results of the Stella Artois 275 mL beer glass bottle.

| *vol* [mL] | $f_-$ [Hz] | $f$ [Hz] | $f_+$ [Hz] | $\Delta f$ [Hz] |
|---|---|---|---|---|
| 0 | 205 | 220 | 234 | 14,5 |
| 50 | 231 | 243 | 261 | 15,0 |
| 100 | 264 | 278 | 296 | 16,0 |
| 150 | 305 | 331 | 354 | 24,5 |
| 200 | 410 | 428 | 445 | 17,5 |
| 250 | 645 | 668 | 703 | 29,0 |

**Table 2:** Measurement results of the Heineken 330 mL beer glass bottle.

| *vol* [mL] | $f_-$ [Hz] | $f$ [Hz] | $f_+$ [Hz] | $\Delta f$ [Hz] |
|---|---|---|---|---|
| 0 | 191 | 202 | 213 | 11,0 |
| 50 | 202 | 221 | 237 | 17,5 |
| 100 | 229 | 242 | 264 | 17,5 |
| 150 | 258 | 277 | 296 | 19,0 |
| 200 | 301 | 326 | 345 | 22,0 |
| 250 | 382 | 420 | 441 | 29,5 |

**Table 3:** Measurement results of the Aurora 1500 mL grape juice glass bottle.

| *vol* [mL] | $f_-$ [Hz] | $f$ [Hz] | $f_+$ [Hz] | $\Delta f$ [Hz] |
|---|---|---|---|---|
| 0 | 127 | 127 | 132 | 2,5 |
| 250 | 137 | 140 | 143 | 3,0 |
| 500 | 153 | 156 | 161 | 4,0 |
| 750 | 175 | 180 | 186 | 5,5 |
| 1000 | 210 | 218 | 226 | 8,0 |
| 1250 | 291 | 296 | 307 | 8,0 |

One can verify that Stella Artois bottle is able to produce musical notes at least from the interval between notes $A_3$ to $A_4$ according to table 3.14 from [2]. This table was used in this work as a reference, allowing to make the correspondence between frequency and musical notes in the scale of equal temperament.

The Heineken bottle can produce musical notes from $A_3$ to $G_4$ within its range (from 202 - 420 Hz). Aurora bottle produces musical notes from $C_3$ to $C_4$, within its frequency range (127 - 296 Hz).

Data-set for each of three investigated bottles were processed in the *Spyder* Python environment, using a numerical fitting script written according to Helmholtz resonator model (6). Fitting results are shown in Figures 7, 8 and 9:

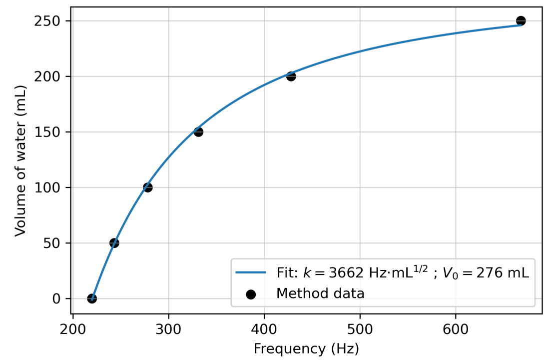


**Figure 7:** Stella Artois glass bottle fitting results from application of the method. $\overline{\Delta f} = 19$ Hz ; $\overline{\Delta vol} = 19$ mL.

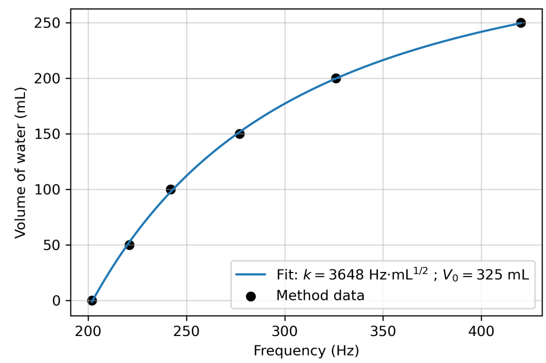


**Figure 8:** Heineken glass bottle fitting results from application of the method. $\overline{\Delta f} = 19$ Hz ; $\overline{\Delta vol} = 27$ mL.

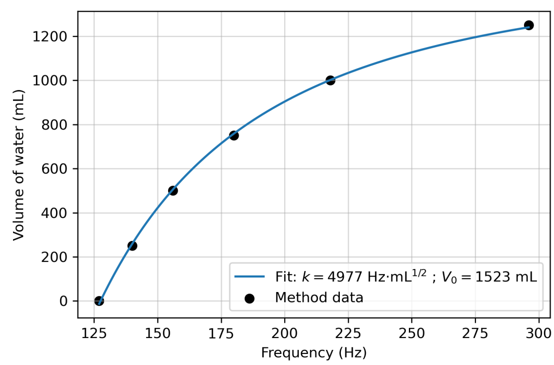


**Figure 9:** Aurora glass bottle fitting results from application of the method. $\overline{\Delta f} = 5$ Hz ; $\overline{\Delta vol} = 45$ mL.

Numerical fits for three investigated bottles proved to be sensible to the empty bottle volume $V_0$ presented on bottle labels, a quick calculation point out to a relative error of 2% at most. Studied bottles presented very smooth data-sets for the tones produced by bottle neck blowing, for our surprise the tendency of data agrees in every detail with the Helmholtz resonator model, even knowing that data taking could depend on the operator attitude. Numerical fit quality reinforces that even complex shaped glass bottles, i. e., more complex geometries, still can be modeled as Helmholtz resonators.

## 5. VALIDATION AND DISCUSSIONS

In order to validate the proposed method, as well as results produced in this work, bottles were tuned using an electronic guitar tuner (Korg CA-1, see Figure 6 and manual [10]). The validation tuning process was done by pouring water inside studied bottle and blowing at its neck until CA-1 tuner displayed precision musical notes tuned. This process was done for musical notes previously mentioned for each bottle in the results section. Once done, one took very carefully and measured (with the graduated cylinder) the amount of water necessary to produce each given note generating data on tables 4, 5 and 6:

**Table 4:** Measurement results from the tunning process with the *Korg* CA-1 for the 275 mL Stella Artois glass bottle.

| $f$ [Hz] | Musical Note (*Korg*) | *vol* [mL] | Method prediction [mL] |
|---|---|---|---|
| 220,0 | $A_3$ | 0 | -1 ± 19 |
| 246,9 | $B_3$ | 48 | 56 ± 19 |
| 261,6 | $C_4$ | 75 | 80 ± 19 |
| 293,6 | $D_4$ | 118 | 120 ± 19 |
| 329,6 | $E_4$ | 152 | 152 ± 19 |
| 349,2 | $F_4$ | 166 | 166 ± 19 |
| 391,9 | $G_4$ | 179 | 188 ± 19 |
| 440,0 | $A_4$ | 205 | 206 ± 19 |

**Table 5:** Measurement results from the tuning process with the *Korg* CA-1 for the 330 mL Heineken glass bottle.

| $f$ [Hz] | Musical Note (*Korg*) | *vol* [mL] | Method prediction [mL] |
|---|---|---|---|
| 220,0 | $A_3$ | 33 | 50 ± 27 |
| 246,9 | $B_3$ | 102 | 106 ± 27 |
| 261,6 | $C_4$ | 134 | 130 ± 27 |
| 293,6 | $D_4$ | 170 | 170 ± 27 |
| 329,6 | $E_4$ | 201 | 202 ± 27 |
| 349,2 | $F_4$ | 211 | 215 ± 27 |
| 391,9 | $G_4$ | 237 | 238 ± 27 |

**Table 6:** Measurement results from the tuning process with the *Korg* CA-1 for the 1500 mL Aurora glass bottle.

| $f$ [Hz] | Musical Note (*Korg*) | *vol* [mL] | Method prediction [mL] |
|---|---|---|---|
| 130,8 | $C_3$ | 31 | 75 ± 45 |
| 146,8 | $D_3$ | 311 | 373 ± 45 |
| 164,8 | $E_3$ | 597 | 610 ± 45 |
| 174,6 | $F_3$ | 699 | 710 ± 45 |
| 195,9 | $G_3$ | 867 | 877 ± 45 |
| 220,0 | $A_3$ | 1013 | 1011 ± 45 |
| 246,9 | $B_3$ | 1128 | 1116 ± 45 |
| 261,6 | $C_4$ | 1174 | 1161 ± 45 |

Comparing results obtained applying the method proposed here and results from validation tuning process, one can see that the model predicts the volume of water with quite good accuracy. Authors would point out that regarding experimental difficulties on proceed data taking from bottle neck blowing, by choice, data should be considered in good agreement with the tuning values of *vol*, even if one must adopt two sigmas limit as confidence level ($2\overline{\Delta vol}$) instead of one sigma (See Figures 10, 11 and 12).

It is important to reinforce that the errors in tables 4, 5 and 6 and the error bars are not standard deviation. They correspond to the error on mouth positioning by the operator, which increases the error of the measurement comparing it to a standard deviation extracted from numerical fitting, for example. Thus, these errors correspond to the values of $\overline{\Delta f}$ and $\overline{\Delta vol}$ calculated as part of the method.

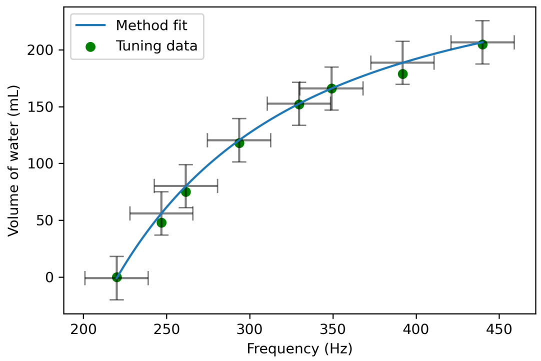


**Figure 10:** Stella Artois glass bottle validation results showing the tuning values of *vol* compared to the predicted values from the method fit.

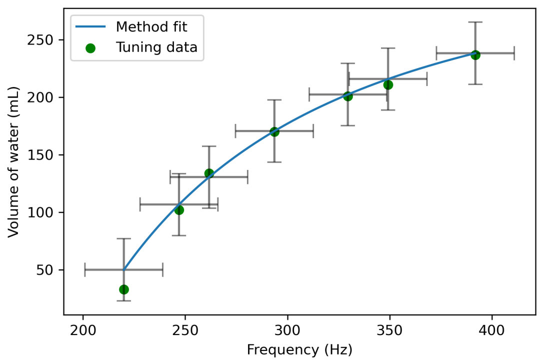


**Figure 11:** Heineken glass bottle validation results showing the tuning values of *vol* compared to the predicted values from the method fit.

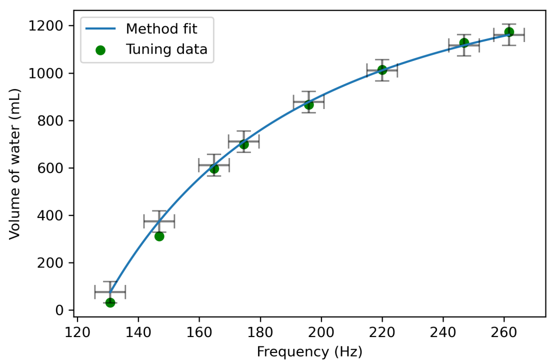


**Figure 12:** Aurora glass bottle validation results showing the tuning values of *vol* compared to the predicted values from the method fit.

## 6. CONCLUSION

Glass bottles as blown wind musical instruments can be understood as Helmholtz resonators and the necessary water volume for a given musical note can be predicted. This paper proposes a numerical method in Python language, that can be used in order to determine parameters $k$ and $V_0$ by a general equation. Free parameters on this equation can be determined throughout a calibration process. The water volume used as filler for the bottles is determined within less than two sigmas ($2\overline{\Delta vol}$), indicating that the method was successful.

The method was applied for three different shaped bottles, showing that the Stella Artois 275 mL beer bottle can produce musical notes in the range of $A_3$ to $A_4$, meanwhile Heineken 330 mL beer bottle can produce musical notes in the range of $A_3$ to $G_4$, and the Aurora 1500 mL grape juice bottle can produce musical notes from $C_3$ to $C_4$. For each bottle, the volume necessary to produce these musical notes within established range (except accidentals) has been tabled and can be used as a reference to tune bottles.

Generic bottles were chosen hoping musicians can use the presented study as a guidance for tuning their sets of bottles as musical instruments. For students, scientists and engineers, authors hope have kepted their attention and eventually instigate on them the reproduction of the experiments.

Finally, a cross check of the developed method come from the fact that parameter $V_0$ adjusted was in clear accordance (less than 2% of error) with the volumes shown in tested bottle labels. Fit of data-set was precise, showing that the model is appropriate to be applied on generic glass bottles.

## 7. ACKNOWLEDGEMENTS

I would like to thank colleagues from the Physics Institute - UFBA and friends whom somehow supported this work by sharing opinions and discussions about it. I would like to thanks LaPO - IF - UFBA itself for providing a healthy scientific environment rich of people, ideas and debates that contribute for producing scientific works and advances in science. Thanks Brazilian CNPq and CAPES for financial support.

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