Water-Sensing Water Bottle

6.2300 Class Project: Final Report
TeamID: RFBottle

Joshua Feliciano
EECS Department
joshfeli@mit.edu

Rachel Raybuck
EECS Department
raydoe@mit.edu

Tiffany Tran
EECS Department
tvtran@mit.edu

***Abstract*—Water is a necessity everyone needs to have, but it is easy to forget to drink. It can also be difficult to keep track of how much one has consumed, especially for young kids or athletic people. We designed a water bottle that would use transverse electric (TE) resonant frequency modes to measure how much water is in the bottle. The sensing technology can be the foundation of a more complete hydration system that tracks the amount of water a user intakes throughout the day.**

I. Introduction & Motivations

While drinking water is a necessary part of life, many people tend not to keep themselves hydrated enough, typically because they forget to drink water. In an article from Harvard, a study was done on children and adolescents that showed that a majority of children were not hydrated enough. Even being mildly dehydrated is associated with health issues, such as lower physical performance and reduced cognitive functioning [1]. As a first step to encourage people to drink more water, we designed a water bottle that would measure how much water is in the bottle using RF electromagnetic waves. The data could then be used by the user to track their hydration goals or could serve as input to another system that would remind the user to drink more, depending on how much water is left in the bottle.

Staying hydrated can help prevent various health issues as water plays a crucial role in the human body. In another paper that focuses on adult dehydration, water is used for various bodily functions, so when it is lost without being replenished, the body can end up developing immobility, diabetes, and renal disease, especially in elderly people [2]. As drinking enough water to crucial to maintain one's health, especially for younger people, there should be more ways to encourage and remind people to drink enough water.

The idea of tracking water consumption is not new and has been done in various ways. One device that was created to encourage people to drink more water is called the WaterCoaster. Instead of using electromagnetic waves to measure how much water is in the container, they instead had a coaster that would measure the weight of the container to track how much the user drank [4]. Another device that is more similar is a water bottle that uses sensors and wires to detect how much water is in the bottle and displays an image of the tree based on the progress the user has made [5].

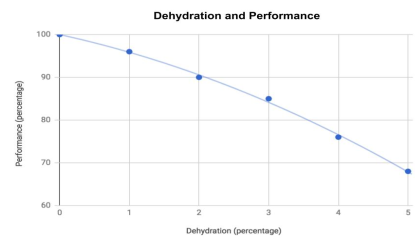

Fig. 1. The above figure shows how exercise and dehydration are correlated. As a person is more dehydrated, their physical performance is shown to decrease. [3]

It is not common to use RF waves to measure an amount of water, but there have been similar techniques for different problems. One piece of equipment from the University of Michigan uses sound waves at a constant frequency to measure the flow rate of the water passing through [6]. While it is not using electromagnetic waves, the idea of using something at a certain frequency is similar to the project. Another technique that also uses sound instead of electromagnetic waves is in an article from MIT News where physicists look at the resonances of fluids of different viscosity [7].

Our overall approach is to use electromagnetic waves and the theory of TE cavity resonator to detect how much water remains in the container, an approach which is more fully described in Section II. We discuss the legality and ethics of this experiment in Section III. We then present our results in Section IV and provide an analysis of them in Section V. Finally, we conclude this report in Section VI.

II. Materials & Methods

We first present some facts and theory [8] [9] that will be helpful in understanding the ideas behind our design. With all the necessary background built up, we will translate the theoretical concepts into explicit designs and calculations, listing the materials necessary for the experiment and showing diagrams along the way. By the end of this section, the reader previously exposed to electromagnetism should have a firm grasp of the core of our project and have enough information to reproduce the experiment.

A. Background

We start with some theory on TE modes of a metal cavity resonator, starting with an air-filled cavity.

If we place two perfectly conducting metal plates a distance L from each other in the presence of a electromagnetic wave electric fields parallel to the plates, boundary conditions require that the electric field at the surface of each conductor be 0. We thus constrain the frequencies of such a wave to be resonant modes f, where the wavelengths λ of waves that can exist between the plates must satisfy $L = m\frac{\lambda}{2} = m\frac{c}{2f}$ for some $m \in \mathbb{N}$ (c is the speed of light in air). Such a resonator is called a $\frac{\lambda}{2}$, or a "short-short", resonator.

For the rest of the analysis, we focus on the case $m = 1$, which yields the fundamental frequency f_0 of the resonator.

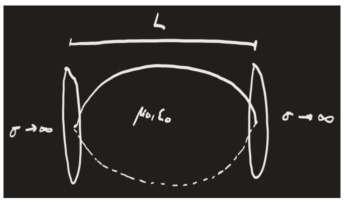

Fig. 2. A depiction of a $\frac{\lambda}{2}$ resonator with the first TE mode excited

What happens if we introduce drinking water between the two plates as a second medium for the wave to travel through? Let us examine the behavior of the resonator at the air-water boundary, with the TE wave incident from air. Drinking water is a non-magnetic material, but its permittivity relative to air is $\epsilon_r \approx 80$ [10]. Thus the impedance of water will be $\eta_w = \sqrt{\frac{\mu_0}{80\epsilon_0}} = \frac{1}{\sqrt{80}}\eta_0 \approx \frac{\eta_0}{9}$ (where η_0 is the impedance of air). If the wave is incident from the air side of the boundary, we will see a reflection coefficient of $\Gamma = \frac{\eta_w - \eta_0}{\eta_w + \eta_0} \approx -\frac{8}{10}$.

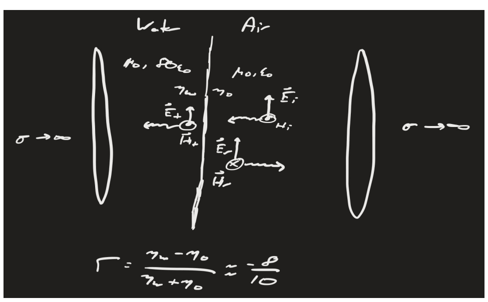

Fig. 3. A depiction of an electromagnetic wave incident on the air-water boundary within a TE short-short resonator

The key takeaway is that we approximate this reflection coefficient to be $\Gamma \approx -1$: we treat the water as a perfect conductor! For a resonator of length $L' < L$, we would expect to see a first-mode resonant frequency f_0' to be quantitatively higher than that of the length-L resonator f_0, due to the relation $L' = \frac{\lambda'}{2} = \frac{c}{2f_0'} < \frac{c}{2f_0}$. If we were to observe such a frequency f_0', then, we should expect to be able to back-calculate to find the effective length L' of the resonator. We can then compare this value to that of L to infer the amount of the space the water takes up within the resonator.

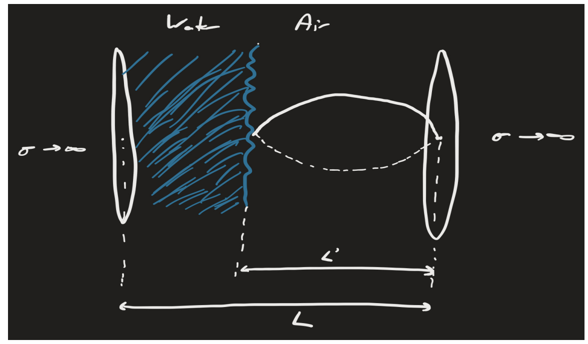

Fig. 4. A depiction of the approximation of water as a short/perfect reflector

The above concepts serve as the main ideas behind our project. In the following subsection we scale up these concepts and make them explicit with our design.

B. Design + Setup

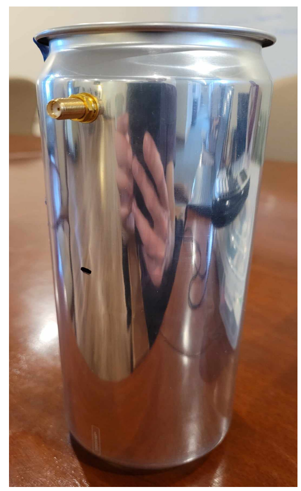

Fig. 5. Our metal can depicted with the with SMA connector

Fig. 6. The copper wire inside the metal can

Our design revolves around an aluminum can of dimensions $L = 19.25$ cm and $r = 4.125$ cm. Aluminum has a conductivity σ of about 40 million Siemens/meter at room temperature [11], so we approximate the aluminum can to be an perfect conductor for the rest of the analysis. Whereas the resonator in the previous subsection was only one-dimensional, we now have a three-dimensional cavity resonator. We thus approximate the can to be a perfect cylinder and analyze the first-mode resonant frequency f_{111} with respect to all three dimensions: radial, axial, and angular (with the intuition following the axial dimension of the can).

Since we scale up to a three-dimensional resonator for this setup, we based our calculations relating resonant frequencies to length of the resonator using an online calculator [13] and calculate $f_1 11$. To excite the can with TE electromagetic waves, we used a copper wire to send and receive electromagnetic waves and then send the signal to a NanoVNA [14]. We started by soldering a 2.7cm copper wire onto a male-male SMA connector, and we inserted the connector into a hole we created toward the top of the can such that the copper wire was oriented normal to the surface of the can (the normal orientation was important to properly excite the TE resonant modes).

(As a note, we chose to go with 2.7cm as that created a $\frac{\lambda}{4}$ antenna with a resonant frequency within the range of expected frequencies of the resonator. While we were more concerned with identifying the resonance frequencies than efficiency, matching the quality factors of the antenna and cavity would allow for a more noticeable dip on the $|S_{11}|$ plot of the VNA, which would allow us to more precisely measure each resonant frequency.)

According to the calculation of the f_{111} frequency, the first-mode frequency for an (empty) air-filled cavity was around 2.3 GHz. Since we expected the f_{111} to increase when water was introduced into the can, we decided to calibrate our VNA to a range of $2.2-4.4$ GHz (4.4 GHz was the maximum measurable frequency [14]) using 2000 sweep points (to measure as finely as possible without freezing our devices).

Once we connected our VNA to the tin-can resonator, we measured the resonant frequency according to the first peak we found in the range in which we were measuring (we found this first peak to be the one that most closely matched the calculated f_{111} freqencies the online calculator predicted). We then took the measured frequency, back-calculated to find the expected volume of water in the can, and compared our results to the volume obtained by pouring the water into a measuring cup.

As we will display in Section IV, we repeated this experiment eight times with varying amounts of water in the can. We discuss our findings in Section V.

III. Legality, Safety and Ethics

The federal government regulates the permitted circumstances for antenna signal transmissions from low-power, non-licensed transmitters [15]. The NanoVNA exciting the antenna in this project consumes less than 3 Watts of power, and its excitation of the antenna consumes and produces much less than that amount as well. This low power level is critical to label the transmitter as "low-power" and apply the related FCC regulations.

The frequency range of the NanoVNA and thus the limits of the antenna's transmit frequencies are 50 kHZ to 4.4 GHz, according to the Specifications section the User Manual [14]. Most of the signal stays in the metal can, but the rest escapes quickly decays and does not travel far enough to interfere with authorized radio communications. This non-interfering behavior complies with FCC regulations for home-built transmitters that are not for sale [15, p. 3]. The project team does not plan to market the project, which means an FCC authorization is not required, according to the same section referenced in the previous sentence.

Federal and local governments also regulate the amount of acceptable metals in drinking water. Given that this project places a copper antenna and soldered joint in close proximity to or entirely submerged in water, these laws are important. Title 40 of the Code of Federal Regulations, section 143.13(a), which is based on EPA guidelines, prohibits the use of leaded solder in commercial products, public water systems, and residential or nonresidential facilities "providing water for human consumption" [16]. The active level for lead in both federal and state standards is 15 parts per billion (ppb) [17] [18]. However, these levels are for drinking water. For bottled water, the FDA has set the limit at 5 ppb [17]. Based on these regulations, the project device does not use leaded solder, which will keep lead levels to an acceptable level and comply with federal laws. The active level for copper allowed by the EPA is 1.3 ppm [17]. Given that copper is used in plumbing, the copper wire antenna should be safe to use as well. A non-toxic impermeable coating over the wire and/or joint may further decrease risks. If the project is pursued further, lead and copper levels would need to be confirmed with water tests.

The aluminum can should be safe to use with drinking water. Radio and microwave frequencies are non-ionizing [23], so bouncing these frequencies off of and/or through the water should not alter the water in a way that would negatively affect users' health. To minimize health risks to the development team (mainly from the solder and copper wire), the team knows not to drink water that has been in the can. Further, to minimize risks of outsiders mistakenly drinking water from it, a notice on the can indicates that it should not be drunk from. Laboratory and "common sense" safety practices were used to mitigate risks.

Regarding the ethics of this project, the most obvious issue would be the safety of the users. They would be directly impacted if preventative sealing over the copper wire and joint fails and copper leaks into their drinking water in unsafe amounts (1.3 mg/L) [17]. This outcome could negatively impact their health, but given that the human body naturally regulates its copper levels [19], it is likely that symptoms would be noticed in sufficient time to avoid permanent health effects [20]. Opting to coat the wire and joints or placing the antenna out of the water and in a closed compartment may be safer for the users. However, the latter design choice would be difficult and likely not conducive to accurately measuring water levels, though this could be explored in the future.

In contrast to negatively affecting users' health, if this project succeeds in encouraging people to regularly drink water, their health may improve. Increased water consumption, combined with other diet changes, may be associated with increased weight loss, for example [21] [22]. This effect could indirectly decrease business with doctors and/or hospitals. While doctors may lose patients and money, hospitals could benefit from fewer spurious cases. The team does not feel responsible for preventing these impacts as our goal is better health for our users. Other water bottle or drink companies may also be negatively affected if people switch to using this device, but the developers again do not feel responsible for mitigating this risk as regular water intake may benefit many.

IV. Results

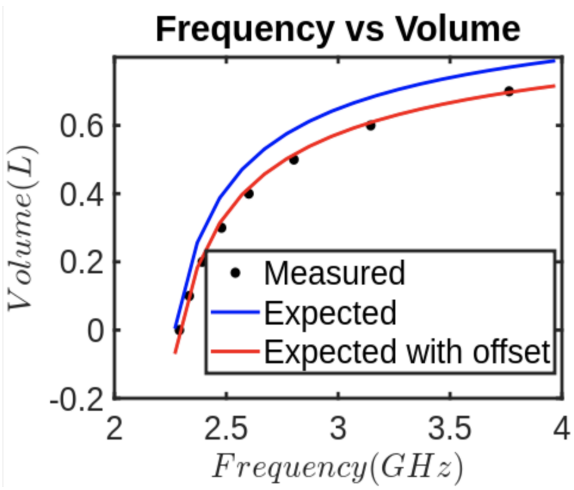

Fig. 7. The above plot shows the difference between the calculated water levels in the can and the measured volumes of water, according to a measuring cup. We show the calculations with and without a calibration offset.

TABLE I
Experiment Results

Measured Frequency (GHz)	Calculated Volume (L)	Measured Volume (L)	Calibrated Volume (L)	Percent Error (%)	Offset Error (%)
2.29025	0.07	0	0	100.00	0.00
2.33427	0.19	0.1	0.11	87.51	13.90
2.39260	0.29	0.2	0.22	46.00	9.20
2.47844	0.40	0.3	0.32	31.82	7.29
2.60060	0.49	0.4	0.42	22.78	4.38
2.80200	0.59	0.5	0.51	17.66	2.94
3.14537	0.68	0.6	0.61	13.74	1.47
3.76388	0.77	0.7	0.70	10.08	0.43

[a]The table shows the measured frequencies and corresponding volumes.

The table shows the frequencies that were measured and the volumes that were calculated and measured. The calibrated volume represents the calculated volume after being offset to fit our system. The percent error is the error between the original calculated volume and the measured volume. The offset error is the error between the calibrated volume and the measured volume.

As shown in the table, the offset error is much larger when the water level is very low. The resonator will also not work properly if the water were to touch the antenna as it would cause the resonant frequencies to be different.

V. Discussion

The results table (Table 1) shows two variations of calculated volume, with the red line representing the theoretical calculations plus an offset. When examining the data, we saw a relatively constant difference between the measured and calculated volume levels, which was roughly the "calculated" volume of water when there was no water in the can. After using this as an offset to calibrate our calculations, we achieved the red line in Figure 7, which has a percent error of 10% (accuracy within 10 mL).

Some parts of the data that made us realize there were limitations in our design were the larger errors we were getting when there was little to no water in the cavity resonator. Errors may have arose due to assumptions of the water and can being perfect conductors and reflection boundaries. The cavity resonator displayed the changes in the resonant frequencies very well in the frequency range we were working in (2.2-4.4 GHz). This behavior is partially due to matching the antenna to approximately a quarter-wavelength of that frequency range. Something that would improve the project if done again is using a more accurate cylinder rather than the one we have that had a smaller radius at the top and bottom of the can. We could also improve the antenna by making it more robust and less resistant to bending.

VI. Conclusions

As our results showed, our water-sensing water bottle accurately measured water volume to within about 10% error (i.e., within 10 mL), with the largest error being 13.90%. We envision our sensing technology to be the first step toward creating a safe, smart water bottle that can encourage users to drink more water, whether simply by providing users with their data or by using it to send reminders to drink.

References

[1] Harvard T. H. C. School of Public Health, "Study finds inadequate hydration among U.S. children," *News*, Jun. 11, 2015. Available: https://www.hsph.harvard.edu/news/press-releases/study-finds-inadequate-hydration-among-u-s-children/

[2] K. Taylor and E. B. Jones, "Adult Dehydration," in StatPearls, Treasure Island (FL): StatPearls Publishing, 2023. [Online]. Available: http://www.ncbi.nlm.nih.gov/books/NBK555956/

[3] U. of H. at M. F. S. and H. N. Program and H. N. Program, "Water and Electrolyte Needs," Aug. 2020. [Online]. Available: https://pressbooks.oer.hawaii.edu/humannutrition2/chapter/16-water-and-electrolyte-needs/

[4] P. Lessel, M. Altmeyer, F. Kerber, M. Barz, C. Leidinger, and A. Krüger, "WaterCoaster: A Device to Encourage People in a Playful Fashion to Reach Their Daily Water Intake Level," in *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems*, in CHI EA '16. New York, NY, USA: Association for Computing Machinery, 2016, pp. 1813–1820. doi: 10.1145/2851581.2892498

[5] University, Gül Kaner Koç, et al. "Grow: Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems." ACM Conferences, 1 Apr. 2018, https://dl.acm.org/doi/abs/10.1145/3170427.3188521.

[6] U. of M. Chemical Engineering Dept., "Velocity – Visual Encyclopedia of Chemical Engineering Equipment," textit Visual Encyclopedia of Chemical Engineering Equipment. 2022. [Online]. Available: https://encyclopedia.che.engin.umich.edu/velocity/

[7] J. Chu, "Physicists capture the sound of a 'perfect' fluid," *M*IT News — Massachusetts Institute of Technology, Dec. 03, 2020. https://news.mit.edu/2020/sound-perfect-fluid-1203

[8] L. Daniel, K. P. O'Brien, J. Notaros, "6.2300 Electromagnetic Waves & Applications" MIT, Undergraduate Course.

[9] S. J. Orfandis, Electromagnetic Waves and Antennas. Piscataway, NJ: ECE Department Rutgers University, 2016. [Online]. Available: https://www.ece.rutgers.edu/ orfanidi/ewa/

[10] D. P. Fernández, Y. Mulev, A. R. H. Goodwin, J. M. H. Levelt Sengers; A Database for the Static Dielectric Constant of Water and Steam. *Journal of Physical and Chemical Reference Data*. 24, 33–70, January 1995. Available: https://doi.org/10.1063/1.555977

[11] J. G. Cook, J.P Moore, T. Matsamura, M. P. Van der Meer, "The Thermal and Electrical Conductivity of Aluminum", Oak Ridge Natl. Lab., Oak Ridge, Tennessee, ORNL-5079, 1975.

[12] R. H. Shreiner and K. W. Pratt,"Primary Standards and Reference Materials for Electric Conductivity," Natl. Inst. Stand. Technol., Gaithersburg, Maryland, Spec. Publ. 260-142, 2004.

[13] LearnEMC. (2023, May 16). *Resonant Frequencies of a Cylindrical Enclosure* [Online]. Available: https://learnemc.com/EXT/calculators/Cavity_Resonance_Calculator/cyl-res.html

[14] NanoRFE. (2023, Apr. 26). *User Manual - NanoVNA V2* [Online]. Available: https://nanorfe.com/nanovna-v2-user-manual.html

[15] Office of Engineering and Technology Federal Communications Commission, "Understanding the FCC Regulations Low-Power, Non-Licensed Tranmitters", OET BULLETIN NO. 63 October 1993. Available: transition.fcc.gov/bureaus/oet/info/documents/bulletins/oet63/oet63rev.pdf

[16] "40 CFR Part 143 Subpart B – Use of Lead Free Pipes, Fittings, Fixtures, Solder, and Flux for Drinking Water." Available: https://www.ecfr.gov/current/title-40/chapter-I/subchapter-D/part-143/subpart-B

[17] "Lead (Pb) Toxicity: What Are U.S. Standards for Lead Levels? — Environmental Medicine — ATSDR," Feb. 22, 2022. Available: https://www.atsdr.cdc.gov/csem/leadtoxicity/safety_standards.html

[18] Massachusetts Dept. of Environmental Protection, "Is there lead in my tap water? — Mass.gov." Available: https://www.mass.gov/guides/is-there-lead-in-my-tap-water.

[19] "Copper in drinking water — Mass.gov." Available: https://www.mass.gov/service-details/copper-in-drinking-water.

[20] N. R. C. (US) C. on C. in D. Water, "Health Effects of Excess Copper," in Copper in Drinking Water, National Academies Press (US), 2000. [Online]. Available: https://www.ncbi.nlm.nih.gov/books/NBK225400/

[21] E. A. Dennis et al., "Water Consumption Increases Weight Loss During a Hypocaloric Diet Intervention in Middle-aged and Older Adults," Obesity, vol. 18, no. 2, pp. 300–307, 2010, Available: https://doi.org/10.1038/oby.2009.235.

[22] E. A. Dennis, K. D. Flack, and B. M. Davy, "Beverage consumption and adult weight management: A review," Eating Behaviors, vol. 10, no. 4, pp. 237–246, Dec. 2009, Available: https://doi.org/10.1016/j.eatbeh.2009.07.006.

[23] "RF Safety FAQ." Available: https://www.fcc.gov/engineering-technology/electromagnetic-compatibility-division/radio-frequency-safety/faq/rf-safety