Water-tracking Water Bottle

6.2300 Class Project: Detailed Plan
TeamID: RFBottle

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***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 electromagnetic waves to measure how much water is in the bottle and notify the user to drink water depending on how much is left inside at various time intervals for people of all ages. The notification will be a light or sound depending on the user and will track the amount of water consumed 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]. To encourage more people to drink water, we designed a water bottle that would measure how much water is in the bottle using electromagnetic waves and remind the user to drink water depending on how much is left inside.

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.

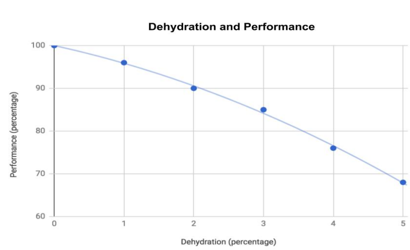

Fig. 1. The above figure shows how exercise and dehydration are correlated. As a person is more dehydrated, their physical performance is shown to decrease. [3]

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].

It is not common to use RF frequency 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 viscosities [7].

Our overall approach is to use electromagnetic waves and frequency to detect how much water remains in the container. We plan to investigate the appropriate locations of the antenna in the approach section of this paper. We will also look at expected resonant frequencies and quality factors at various water levels in the results section of this paper.

II. Approach

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 then present our design and its variations that we will explore in experiments, which will help determine the best way to accurately measure the water level in a can. We will also list the materials necessary for the experiment and show diagrams along the way to aid in the explanation. By the end of this section, the reader previously exposed to electromagnetics should have a firm grasp of the core of our project and should have enough information to reproduce the experiment.

A. Background

We start with some facts about water and 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).

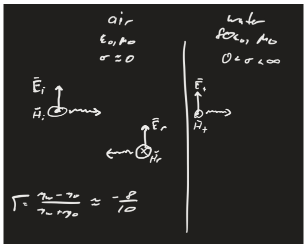

Fig. 2. A depiction of an electromagnetic wave incident on an air-water boundary

We can use this information to analyze the behavior of an incident electromagnetic wave that encounters an air-water interface. If the wave is incident from the air side of the boundary, part of the wave will transmit through the boundary into the water while the rest will reflect into the air. Specifically, the reflection coefficient Γ will equal $\Gamma = \frac{\eta_w - \eta_0}{\eta_w + \eta_0} \approx -\frac{8}{10}$. Thus roughly $\frac{8}{10}$ of the intensity of the wave will reflect off the water and propagate back into the air.

The remaining part of the wave that does not reflect will transmit into the water. Drinking water is a lossy dielectric with a conductivity of $\sigma = 5.5 \times 10^{-6}$ Siemens/meter [11], so the part of the wave transmitted into the water will see some attenuation. One could imagine that, if there was a way for a wave to travel through air, hit the air-water boundary, and then reflect off another surface to again encounter the boundary, the wave would gradually lose power as the wave kept encountering the air-water interface. Indeed, this might be achieved by placing some perfect metal conductor for the reflected wave to then reflect again and travel once more toward the air-water interface.

An electromagnetic wave might encounter such a metal surface in a structure like a TE resonator. If we place two perfectly conducting metal plates a distance L from each other in the presence of a TE electromagnetic wave, the 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, where the wavelengths λ of waves that can exist between the plates must satisfy $L = m\frac{\lambda}{2}$ for some $m \in \mathbb{N}$ (such a resonator is called a $\frac{\lambda}{2}$, or a "short-short", resonator).

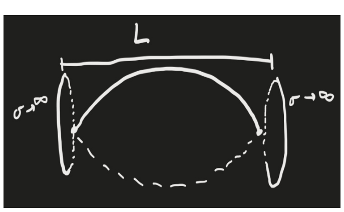

Fig. 3. A depiction of a $\frac{\lambda}{2}$ resonator with the first TE mode excited

How might we send such a wave into the resonator structure? We could place an antenna within the structure to excite electromagnetic waves at various frequencies. We could then calculate the quality factor of the antenna and match it to that of the resonator (and add some loss to the resonator, such as using metals with finite conductivity σ), to best excite the resonant frequencies of the TE resonator and thus deliver a lot of power to the resonator from the antenna. With such a level of power being delivered to the resonator, we could send a wave with high power to interact with materials within the resonator, such as an air-water boundary.

All the above concepts and theory contribute to the design of our water level sensor in some way. We tie these results together explicitly in the next subsection.

B. Design

Our design revolves around a metal can of dimensions $L = 19.25$ cm and $r = 4.1$ cm. The metal has some loss (i.e., finite σ), but since it is a good conductor we will approximate it to be ideal for most of the analysis. We can insert a small copper antenna (on the order of centimeters) normal to the circumference of the can where, depending on the position and length of the antenna, we can excite certain TE modes and achieve higher or lower power delivery than other positions.

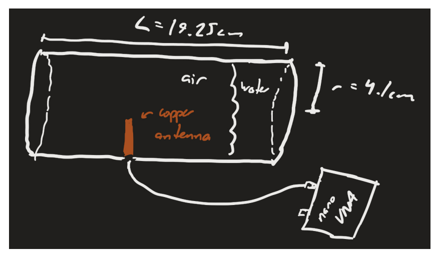

Fig. 4. Our setup including the tin can, the copper wire, the SMA cable, and the NanoVNA [12].

The can acts as a cavity resonator, with an air-filled inner cavity surrounded by "short circuits" (i.e., a short-short resonator in all 3 dimensions). Since this is a short-short resonator with some loss, the structure will have some nominal resonant frequencies for each TE mode as well as a finite (internal) quality factor. We can insert a small copper antenna (on the order of centimeters) normal to the circumference of the can where, depending on the position and length of the antenna, we can excite certain TE modes and achieve higher or lower power delivery than other positions.

However, when there is some water in the can, we expect the resonant frequencies for each TE mode and the quality factor to change. We take a first-order approximation for the reflection coefficient $\Gamma_{\text{air-to-water}} \approx -0.8 \approx -1$, thus approximating the water in the can to be an effective short circuit. Thus the effective length of the resonator L_{eff} would change, and so would the resonant frequencies. We also expect the quality factor to change, since the water would attenuate the signal with each transmission and thus create more loss within the structure (power dissipation is inversely related to internal quality factor). We thus plan to examine the deviations from the nominal resonant frequency and quality factor of the empty tin can resonator in the presence of water to infer how much water is in the can.

The materials we plan to use include the metal can and a copper wire for the antenna (with a wire cutter to trim its length). We will send electromagnetic waves to the antenna using a NanoVNA v2 [12] with SMA connectors, with the connector inserted into the cavity of the can and the antenna soldered onto the connector (image shown). We can use a material like plumber's putty to seal the gap in the can created by the SMA connector. We may also investigate using a coating for the antenna to minimize the contact between water and the copper and lead solder.

We plan to start by creating a lengthwise slit into the can and inserting the antenna in different places to see how the resonant frequencies and quality factor changes with antenna placement. Once we choose a location for the antenna, we will use the NanoVNA to excite the can with various frequencies and plot functions of water level versus frequency and quality factor (more detail in Section IV).

With this setup and experiment plan, we hope to produce accurate estimates of water levels in a metal can for the user.

III. Legality, Safety and Ethics

The federal government regulates the permitted circumstances for antenna signal transmissions from low-power, non-licensed transmitters [13]. 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 [12]. 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 [13, 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" [14]. The active level for lead in both federal and state standards is 15 parts per billion (ppb) [15] [16]. However, these levels are for drinking water. For bottled water, the FDA has set the limit at 5 ppb [15]. 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 [15]. 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 [17], 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 metals leak into their drinking water in unsafe amounts. This outcome could negatively impact their health, possibly limiting their ability to work or provide for their family. Opting to coat the wire and joints may have to be the compromise. Placing the antenna out of the water and in a closed compartment may be safer for the users, but that design would be difficult and likely not conducive to accurately measuring water levels.

In contrast to negatively affecting users' health, if this project succeeds in encouraging people to regularly drink water, their health may improve. 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 the goal should be better health for the users, rather than feeding a struggling medical system. 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 would benefit many.

IV. Results

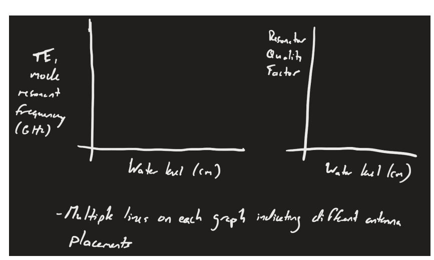

Fig. 5. Expected measurements of TE-mode resonant frequencies and quality factor versus (known) water levels

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