

Characterization of Gear Oil Degradation via Microwave Cavity

6.013 Class Project

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Abstract—Mechanical gearboxes are frequently used in applications requiring both high reliability and long lifespans. Lubrication failure can cause rapid onset mechanical failure, leading to automotive accidents or equipment damage. Additionally, the lubricant is difficult to characterize in-situ and expensive to replace. To measure the contamination from water and wear debris, the use of a microwave cavity resonator within the gear housing is proposed. A model resonator in oil is constructed, and its return loss is characterized as a function of contaminant levels. Measurable trends in resonant frequency can be observed for water-based contaminants, providing an inexpensive, continuous measurement of oil lifetime without machine downtime or chemical reagents.

I. INTRODUCTION & MOTIVATIONS

Numerous systems require the use of lubricated gearboxes, as highlighted in Figure 1. Unfortunately, current lubricant maintenance schedules are built around approximate load conditions. For instance, a vehicle gearbox may require fresh lubricant every few thousand miles, or an industrial gearbox may require an oil change every few hundred hours. [1] [2] Methods of determining gear wear *a priori* are largely based on previous empirical data, so practical maintenance schedules are driven by manufacturer testing using estimated loads. [3] This approximation, and the disruptive inspections required do not yield the optimal replacement schedule for each gearbox relative to its load environment. This leads to excessive cost and waste, of which over 750 million liters of lubricant oil are improperly disposed of each year. Thus, both economic and environmental concerns motivate the development of better characterization techniques. [4] [5]

Existing solutions to this problem are primarily optical. By passing a laser through a sample of oil, it is possible to estimate the number of trapped particles, but not the level of water contamination. [6] Laboratory chemical analyses are also used, as well as cruder tests involving mere visual inspection for wear debris. [7] Neither method permits ‘on-line’ measurement of lubricant performance, and are resultingly expensive in terms of both equipment and machine downtime.

The idea of measuring physical properties via a resonant cavity is not new. A similar idea has been used to measure the amount of water in crude oil (the water-liquid ratio or “water cut”). One approach used a resonator on the side of

a flowing pipe, and measured effects on the fringe fields of the resonator. [8] Another approach, used in commercial measurement devices, is to compute the conductivity by measuring changes in the resonant frequencies of a pipe carrying crude oil. [9] Resonant cavities have also been used to measure the mass of rapidly moving hydrogen pellets for fusion ignition, or for pharmaceutical quality control, and thus these cavities form a flexible solution to diverse problems. [10] [11]

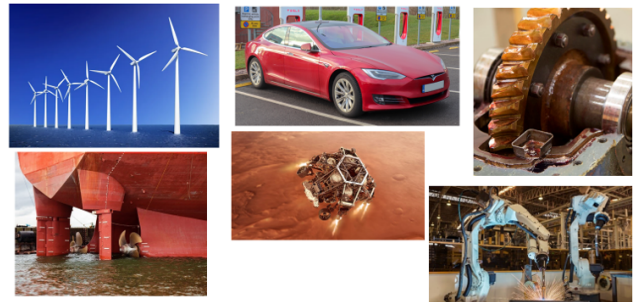


Fig. 1. Examples of applications dependent on effective gearbox lubrication. [12] [13] [14] [15] [16] [17]

II. APPROACH (AKA MATERIALS & METHODS)

The primary contaminants in gear lubricant are wear debris, abrasively removed from the gears themselves, and water. [18] [19] These contaminants affect several properties of the oil, such as the permittivity and conductance. To quantify the effects of these contaminants, vegetable oil is used as a substitute for ExxonMobile SpectraSyn Plus™ synthetic gear oil, needed due to supply issues obtaining gear oil at present. AISI 4140 stainless steel filings and tap water are then mixed into the oil within the resonator.

A cylindrical cavity resonator submerged in a lubricant bath was used. The resonator was driven using a short monopole antenna, in turn powered by the NanoVNA, a consumer-grade Vector Network Analyzer. The signal was swept in frequency between 1 GHz and 4 GHz, such that the resonant frequencies and qualities were measurable. As water or steel are mixed into the lubricant, the bulk permittivity and bulk conductivity of the medium change, affecting resonant performance. These

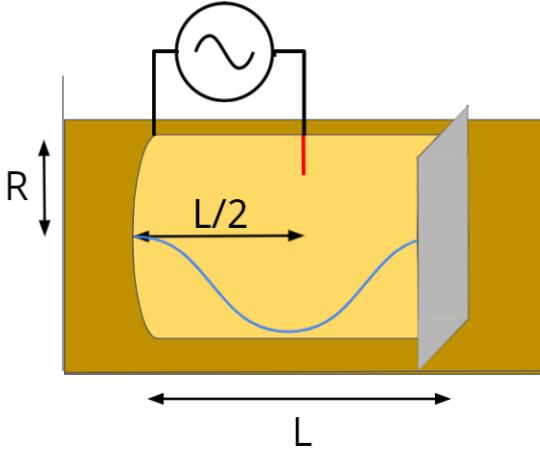


Fig. 2. A diagram of the cavity resonator submerged in gear oil. The first mode is visible as the blue curve, and an insert antenna into the resonator as a red line linked to a driving voltage source.

parameters affect the unloaded quality factor Q_0 and the resonant frequency f_{nml} of a given mode, and thus the measurable resonator parameters are related to physical parameters.

The resonator was designed to excite the TE_{111} mode, which has the lowest cutoff frequency. The probe's orientation forces a transverse electric mode, where the axial electric field is sinusoidal and the radial electric field follows a Bessel function. Modeling the resonator as a perfect cylindrical cavity with finite conductivity metal walls and a homogeneous dielectric, its resonant frequencies are found via equation 1, with relative dielectric ϵ_r , speed of light c , radius R , length L , mode numbers m , n , and l , and p'_{nm} the m th root of the first derivative of the n th Bessel function of the first kind. [20]

$$f_{nml} = \frac{c}{2\pi\sqrt{\epsilon_r}} \sqrt{\left(\frac{p'_{nm}}{a}\right)^2 + \left(\frac{l\pi}{L}\right)^2} \quad (1)$$

A tin-coated steel can was used, with radius $R = 32.5$ mm, and length $L = 65$ mm. The top was removed to allow the oil within the can to be easily replaced, and then re-sealed with an aluminum block to create an electrical short on both ends. A common PAO oil, ExxonMobile SpectraSyn Plus™, has a dielectric constant of 2.1 [21], and other sources suggest it as 2.3. [22] [23] [24] Based on these findings, vegetable oil's dielectric constant of 2.5 makes it a good substitute. [25] Using equation 1, the nominal resonant frequency of the TE_{111} mode is $f_{111} = 2.25$ GHz, in the middle of the VNA's bandwidth.

The resonant frequency of the TE_{111} mode is evident from an S_{11} plot. The half-power bandwidth Δf yields the loaded quality factor $Q_L = \frac{f}{\Delta f}$; however, coupling effects make Q_L differ from the unloaded quality Q_0 , as shown in equation 2:

$$\frac{1}{Q_0} + \frac{1}{Q_E} = \frac{1}{Q_L} \quad (2)$$

To determine the unloaded quality factor, the fact that the resonant system draws a circle on a Smith chart is used. First,

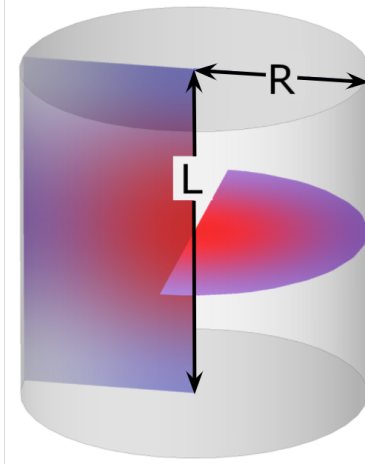


Fig. 3. A qualitative description of the radial and axial components of the dominant TE_{111} mode excited in the resonator.

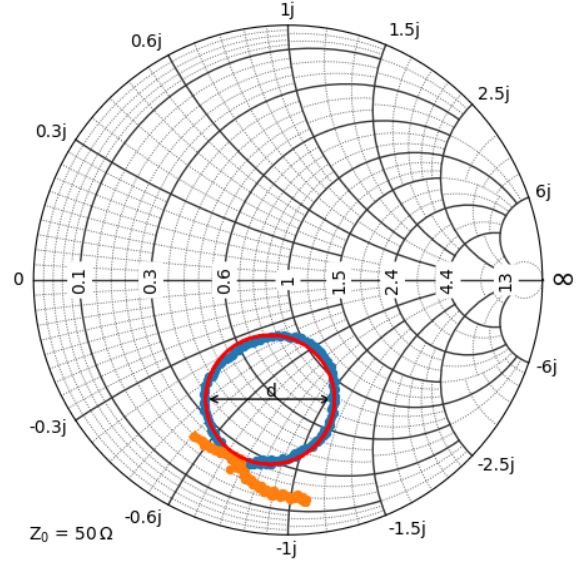


Fig. 4. S_{11} for a sample resonator, plotted on a Smith chart. The raw data is trimmed such that the resulting points (blue) make a circle, to which a least-squares circle fit (red) is applied. The resulting diameter d is used to determine the coupling coefficient and Q_0

the points outside of the circle are removed. Then, applying the method proposed by Shadid et. al., a least-squares regression is conducted to determine the circle's position and diameter d , as seen in Figure 4. [26] Using d , the coupling coefficient κ is calculated, and thus Q_0 can be determined via equations 3 and 4.

$$\kappa = \frac{d}{2 - d} \quad (3)$$

$$Q_0 = Q_L(1 + \kappa) \quad (4)$$

Additionally, to determine the resonator's sensitivities to material properties, the unloaded quality factor was linked to the dielectric loss tangent. First, note the quality of the

can walls (Q_c) and the dielectric (Q_d) together constitute the unloaded quality in equation 5.

$$\frac{1}{Q_c} + \frac{1}{Q_d} = \frac{1}{Q_0} \quad (5)$$

The Q_c for the TE_{111} mode was then found via equations 6a and 6b, with free-space permittivity ϵ_0 , tin-conductivity σ_t , and A defined via 6a: [20]

$$A = \frac{1 - \frac{1}{(p'_{11})^2}}{\frac{L}{2} \left(1 + \left(\frac{\pi R}{L(p'_{11})^2} \right)^2 \right) + \frac{R^3 \pi^2}{(L p'_{11})^2} \left(1 - \frac{1}{(p'_{11})^2} \right)} \quad (6a)$$

$$Q_c = \frac{(\pi f_{111})^{2.5} \epsilon_r R^3}{c^3 (p'_{11})^2} \sqrt{\frac{\sigma_t}{\epsilon_0}} A \quad (6b)$$

Finally, equation 7 relates the dielectric conductivity σ_d to the loss tangent and Q_d , such that equations 5 through 7 can be combined to find the conductivity as a function of the unloaded quality factor, or vice-versa. [20]

$$Q_d = \frac{1}{\tan \delta} = \frac{2\pi f_{111} \epsilon_0 \epsilon_r}{\sigma_d} \quad (7)$$

III. LEGALITY, SAFETY AND ETHICS

The primary legal risk is compliance with Federal Communications Commission (FCC) transmission regulations. Over a range of 1 GHz to 4 GHz, FCC regulations for unlicensed, low power transmitters permit a maximum of 500 μ V per meter at 3 meters. [27] Since the NanoVNA's default power of -15 dBm (31 μ W) is used, compliance is not an issue. [28]

For personal safety, vegetable oil is of minimal concern, as is soldering. According to its Material Safety and Data Sheet, the oil's only danger is flammability, and this was ameliorated by maintaining distance from the soldering iron and any other heat sources. [29] Similarly, eye protection while soldering, ventilation, and observance of MIT policies is sufficient to safely assemble all components. [30]

To a broader population, the experiment itself and its consequences could have adverse effects. Directly, the oil used for testing must be properly disposed of, which was done in MIT's Edgerton Center. Indirectly, better gear oil management policies will harm oil manufacturers' sales, decreasing demand. This is ethically manageable, however, in the name of environmental protection, technological innovation, and overall economic growth.

Far more perilous is the responsibility to rigorously test any derivation of this work used in life-critical applications. Lubrication failure and consequent mechanical binding or fracture can have deadly effects. [31] If this in-situ technology is used to guarantee lubricant safety, than it becomes the technology's developers' moral imperative to ensure its efficacy in such contexts. This requires characterizing its limitations and communicating them with any developers using the sensor, as well as more generally publicizing these warnings.

IV. RESULTS

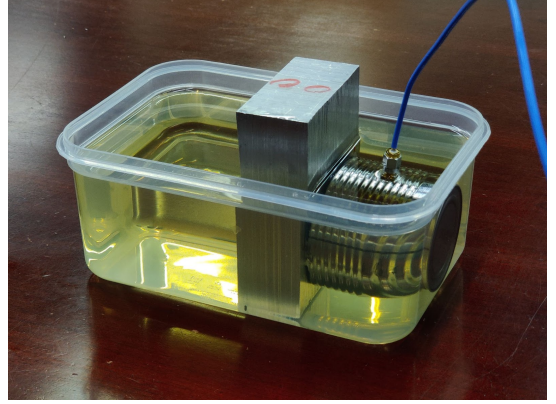


Fig. 5. The cavity resonator submerged in oil. A movable aluminum block allows the oil to enter and exit the cavity as contaminants are added. The SMA cable on the right connects to the NanoVNA.

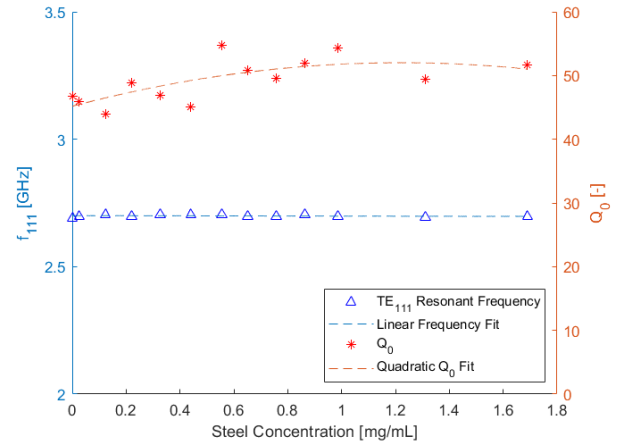


Fig. 6. Plotted data for measurements of unloaded Q_0 and f_{111} at various steel filing concentrations within the oil. The resonant frequency is essentially unchanged and a weak quadratic trend is observed in Q_0 .

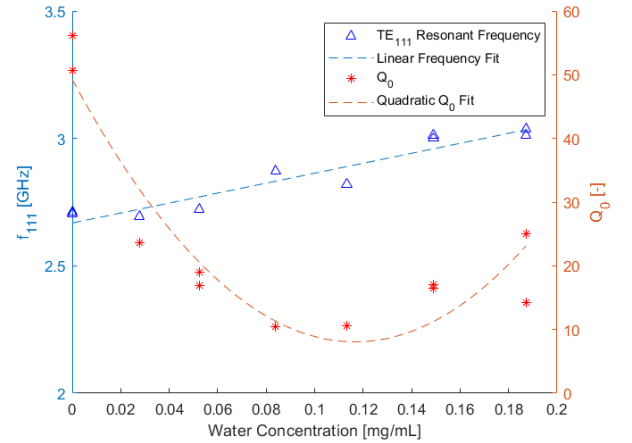


Fig. 7. Data for variable water-oil mixtures, with calculated f_{111} frequencies and Q_0 values. Once again, a weak quadratic trend for the quality can be seen, but an upwards sloping linear correlation between water concentration and f_{111} is present with a coefficient of determination of 0.88.

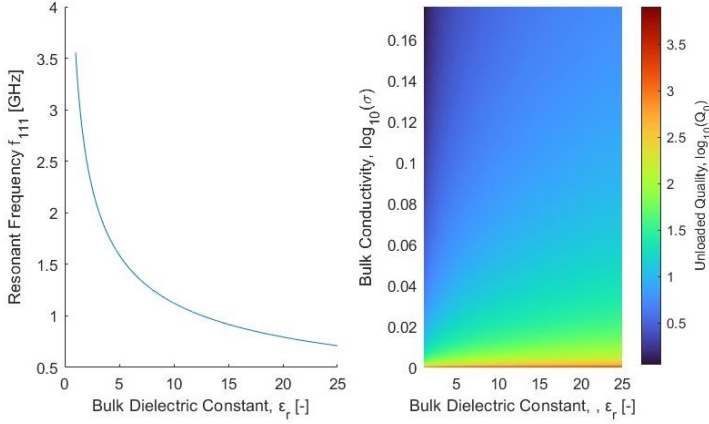


Fig. 8. Using the perfect cavity equations established in section II, bulk dielectric constants and conductivities are swept with the geometry used. (a) The f_{111} frequency is purely a function of ϵ_r , and changes rapidly with increasing dielectric constant. (b) The nominal unloaded quality factor depends on both ϵ_r and σ , but drops off rapidly with increasing conductivities, as is displayed in the heat-map.

TABLE I
POTENTIAL CONTAMINANTS [32] [33]

Type	Typical ϵ_r	Typical σ (μ S/cm)
Water	80	0.0005 — 0.05
Steel	1	7.56×10^6
Aluminum	1	39.69×10^6
Copper	1	59.6×10^6

V. DISCUSSION

In Figure 7 a strong trend between resonant frequency and water concentration is observed. The cavity resolution appears to be below a mass fraction of 0.01%, which allows for detection of typical gear oil water concentrations, around 0.02 - 0.06%. [19] Surprisingly, the direction of the trend line is such that resonant frequency increases with water concentration. This seemingly contradicts the analysis done in Figure 8, which indicates that resonant frequency should instead decrease as the bulk dielectric constant increases. A potential explanation is that since oil floats on water, an interface forms between the two liquids in the resonator. As the tap water used is far more conductive than the oil, it is hypothesized that boundary conditions on the electric field exist on the oil/water interface, and not the bottom of the can. This would cause the electrical length of the can to shorten, and hence the frequency to increase as shown.

In an actual gearbox, the spinning gears would cause turbulent flow within the mixture, alleviating these concerns. Additionally, the resonator had to be sealed with the aluminium block, and the block made inconsistent contact with the top of the can, which could result in variance between runs. If this system were to be implemented within a gearbox, it would most likely be a completely sealed can, with perforations on the side to enable oil to pass through. This would eliminate issues with variance in the seal.

Interestingly, the introduction of steel filings had little effect on the resonator. This is believed to be because the concentrations of materials do not cause the bulk material properties to change significantly. At microwave frequencies the dielectric constant of steel becomes comparable to that of the oil, resulting in no change to the bulk dielectric constant. [34] Similarly, Figure 8 demonstrates that the resonator is not particularly sensitive to changes in bulk conductivity provided by the filings. Q_0 does not change appreciably with bulk conductivity, unless the conductivity is very low - meaning the high conductivity of the metal filings cannot influence the resonator's performance.

Physical limitations of the resonator aside, there are several possible sources of error in the experiment. First, the method used for finding the unloaded quality factor is somewhat sensitive to noise. There are more advanced algorithms for extracting the quality factor, such as the QZERO program, which also provides an error range for the resulting quality factors. [35]. Second, the can originally contained tomato soup, and so contained a food-safe coating. The can also has corrugated sides, which is not modelled in the analysis.

Even if a perfect measurement of Q_0 and f_{111} was possible, the weak or counter-intuitive trends observed could reduce the feasibility of this kind of sensor. It is possible that the effect of multiple contaminants could cancel each other out, causing a heavily contaminated oil to appear identical to clean oil. The feasibility of this sensor could be better surveyed by testing more contaminants in conjunction to see if this behavior is possible. Further developers of this technology would have a moral obligation to explore these effects in order to guarantee that the oil is not falsely measured as clean in life-critical applications.

VI. CONCLUSIONS

Detection of water mass fractions on the order of 0.01% in oil is demonstrated using the resonator, but steel is undetectable with the apparatus used. While this limits the device's current relevance, water measurement alone can resolve real-world contamination levels, and allows for an accurate and cost-effective sensor for water-based contaminants. [19] Future work is still required to characterise non-metallic, non-water-based contaminants and develop reliable sensing of total oil contamination.

REFERENCES

- [1] AAA Automotive, "How Often Should You Change Engine Oil". <https://www.aaa.com/autorepair/articles/how-often-should-you-change-engine-oil>
- [2] Altra Motion, "Large Gearbox Maintenance and Lubrication", November 13, 2012. <https://www.altramotion.com/newsroom/2012/11/large-gearbox-maintenance-and-lubrication>
- [3] American Gear Manufacturers Association, "Fundamental Rating Factors and Calculation Methods for Involute Spur and Helical Gear Teeth", January 1996. <https://wp.kntu.ac.ir/asgari/AGMA%202101-C95.pdf>
- [4] Weinstein, Norman J., "Waste Oil Recycling and Disposal", August 1974. <https://nepis.epa.gov/Exe/ZyPDF.cgi/910235S1.PDF?Dockey=910235S1.PDF>
- [5] Environmental Protection Agency, "Common Wastes & Materials", February 21, 2016. <https://archive.epa.gov/wastes/conserve/materials/usedoil/web/html/oil.html>

- [6] Spectro Scientific, "Guide to Particle Measurement Techniques", October 25, 2017. <https://www.spectrosci.com/resource-center/lubrication-analysis/literature/e-guides/guide-to-measuring-particles-in-oil/>
- [7] Muller, Jane; Errichello, Robert, "How to Inspect a Gearbox", February 2012. <https://www.machinerylubrication.com/Read/28765/how-to-inspect-a-gearbox->
- [8] Sharma, P. et al., "A Microwave Cavity Resonator Sensor for Water-In-Oil Measurements", January 21, 2018. https://dspace.lib.cranfield.ac.uk/bitstream/handle/1826/13041/microwave_cavity_resonator_sensor-2018.pdf
- [9] Nyfors, Eddie G., "Conductivity measurements", July 7, 2019. Patent. <https://patents.google.com/patent/US20150346117A1/en>
- [10] So/rensen, H. et al., "A microwave cavity for measurement of the mass of hydrogen pellets", June 4, 1998. <https://aip.scitation.org/doi/pdf/10.1063/1.1141604>
- [11] Nohlert, Johan, "Microwave measurement techniques for industrial process monitoring and quality control", 2018. https://research.chalmers.se/publication/500655/file/500655_Fulltext.pdf
- [12] England, Rachel, "Denmark's ambitious wind power plans include giant 'energy islands'", May 21, 2020. <https://www.engadget.com/denmarks-ambitious-wind-power-plans-include-giant-energy-islands-120528164.html>
- [13] Wikimedia Commons, "2018 Tesla Model S 75D", February 20, 2019. https://commons.wikimedia.org/wiki/File:2018_Tesla_Model_S_75D.jpg
- [14] Ghosh, Subhdeep, "Understanding Design Of Ship Propeller", January 8, 2021. <https://www.marineinsight.com/naval-architecture/design-of-ship-propeller/>
- [15] Chow, Denise, "NASA's Mars rover is minutes away from a nail-biting landing attempt", February 18, 2021. <https://www.nbcnews.com/science/space/nasas-mars-rover-minutes-away-nail-biting-landing-attempt-rcna280>
- [16] Lubrication Engineers, "Applications". <https://www.lubricants.com/applications/>
- [17] Industrial Automation Asia, "Controlling Robotic Arms". <https://www.iaasiaonline.com/controlling-robotic-arms-2/>
- [18] Fitch, Bennet, "Anatomy of Wear Debris". <https://www.machinerylubrication.com/Read/29537/wear-debris-anatomy>
- [19] Noria Corporation, "Water in Oil Contamination", July 2001. <https://www.machinerylubrication.com/Read/192/water-contaminant-oil>
- [20] Pozar, David M., "Microwave Engineering, 4th Edition", Hamilton Printing, 2012.
- [21] ExxonMobil Chemical, "SpectraSyn Plus™ Polyalphaolefins (PAO)", February 2006. https://www.tri-iso.com/documents/exxonmobil_chemical_spectrasyn_plus_Brochure.pdf
- [22] Underwriters Laboratory, "Polyolefin Typical Properties Generic PAO". <https://plastics.ulprospector.com/generics/38/c/t/polyolefin-properties-processing/sp/2>
- [23] Gao, Zhisheng et al., "Low conductivity lubricating oils for electric and hybrid vehicles", April 12, 2018. <https://patents.google.com/patent/US20180100114A1/en>
- [24] Lindner, Michael, "Oil Condition Monitoring Using Electrical Conductivity", June 2013. <https://www.machinerylubrication.com/Read/29407/oil-condition-monitoring>
- [25] Spohner, Milan. "Study of the dielectric properties of vegetable oils and their constituents", June 2016. <https://ieeexplore.ieee.org/document/7530478>
- [26] Shahid, S., et al., "Reflection type Q-factor measurement using standard least squares methods", IET Microwaves, Antennas & Propagation, March 31, 2010. <https://www.proquest.com/docview/1636702505/fulltextPDF/696EE812F6A4F96PQ/1?accountid=12492>
- [27] Federal Communications Commission, "Understanding the FCC Regulations for Low-Power, Non-Licensed Transmitters", October 1993. https://transition.fcc.gov/Bureaus/Engineering_Technology/Documents/bulletins/oet63/oet63rev.pdf
- [28] HCXQS Group; OwOComm, NanoVNA GUI, 2021. <https://github.com/nanovna-v2/NanoVNA-QT>
- [29] Fisher Science Education, "Safety Data Sheet - Vegetable Oil", February 9, 2015. https://beta-static.fishersci.com/content/dam/fishersci/en_US/documents/programs/education/regulatory-documents/sds/chemicals/chemicals-v/S25622.pdf
- [30] Massachusetts Institute of Technology, "EECS Department Lab Safety Lecture", April 12, 2018. <https://techtv.mit.edu/videos/32364-eeecs-department-lab-safety-lecture>
- [31] Rashid, Hamad et al., "Helicopter MGB Oil System Failure Analysis Using Influence Diagrams and Random Failure Probabilities", January 2015. https://www.researchgate.net/publication/270764391_Helicopter_MGB_Oil_System_Failure_Analysis_Using_Influence_Diagrams_and_Random_Failure_Probabilities
- [32] Engineering Toolbox, Dielectric Constants of Liquids, 2008. https://www.engineeringtoolbox.com/liquid-dielectric-constants-d_1263.html
- [33] Engineering Toolbox, Electrical Conductivity of Elements and other Materials, 2008. https://www.engineeringtoolbox.com/conductors-d_1381.html
- [34] O'Brien, Kevin P., "6.013 Electromagnetics & Applications" MIT, Undergraduate Course Office Hours, May 2021.
- [35] Kajfez, Darko. "Q factor measurements, analog and digital", September 17, 1999. <https://people.engineering.olemiss.edu/darko-kajfez/assets/rfqmeas2b.pdf>