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Modeling of Detection of Water Contamination Located in Diesel Tanks using Phase Change of FMCW Radar

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Abstract

Water contamination in diesel storage tanks presents serious operational and financial risks in automotive, marine, and industrial applications. Water intrusion—resulting from condensation, leakage, or diesel's hygroscopic nature—can lead to microbial proliferation, corrosion, and fuel system damage. Bacteria and fungi thrive at the fuel-water interface, forming biofilms that clog filters and deteriorate fuel quality. Additionally, chemical reactions between water and sulfur compounds in diesel produce corrosive sulfuric acid, accelerating tank degradation. In high-pressure fuel systems, water droplets can also cause injector malfunction. Traditional detection techniques, such as manual inspections, chemical dispatch, and capacitive sensors, fall short in providing accurate, real-time contamination assessment. These limitations have driven growing interest in Frequency-Modulated Continuous-Wave (FMCW) radar as a reliable, non-invasive sensing alternative. FMCW is a continuous -wave radar that transmits a frequency-modulated chirp and analyzes the returned echo to detect material interfaces[1, 2,3]. This study aims to address the challenge of dual-level liquid detection—accurately determining both the diesel surface and underlying water contamination—by leveraging enhanced signal processing techniques to improve measurement resolution and reliability in practical environments.

Keywords: Diesel Fuel Tanks; FMCW Radar; Liquid Level Measurements; Water Contamination.

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1. Introduction & Problem Statement

Water contamination in diesel fuel tanks is a widespread yet critical issue that can lead to engine failure, corrosion, and expensive maintenance. Existing detection methods are often unreliable, invasive, or cost-prohibitive for routine monitoring. This thesis investigates an alternative solution based on radar technology—specifically, Frequency-Modulated Continuous-Wave (FMCW) radar—as a non-contact, accurate method for detecting water contamination in diesel tanks.

The initial concept was straightforward: could radar technology, commonly used in automotive and aerospace systems, be adapted to detect water accumulation in fuel environments? This question guided the research through a process of understanding how radar signals propagate through and reflect off layered media such as diesel and water. The work involved modeling electromagnetic interactions, conducting experiments, and refining signal processing techniques to improve detection accuracy.

As clearly stated in key challenges included dealing with material property uncertainties and ensuring the system could reliably distinguish between fuel and water under practical conditions, in[1] it successfully detected of state parameters fluctuation of gaseous media using a mm-Wave FMCW radar, and also in[4] it paved the way for detection of a fluid when the FMCW radar wave can pass through a wooden obstacle . In[5] it used the power of sensitivity of FMCW Radar to draw the patterns made by acoustic signal below the water level for river surface analysis in [6] [7] FMCW radar was a key player in surface mapping, also in [8 ,3] and [9] it is clear that the limited bandwidth is not a roadblock it have a high precision later level measurement, FMCW radar can be high immune toward dust and water vapor which enables high range of working environment [10]. The outcome is a promising approach for real-time, non-invasive fuel monitoring that offers potential benefits for transportation, storage, and industrial applications where fuel quality is critical. The criticality of the diesel as hazardous fluid [11,12] forced us to double check using 2 simulation methods before starting any practical lab measurement

2. Material and Method

Frequency Modulated Continuous Wave (FMCW) radar is a sophisticated radar technique that operates by transmitting a frequency-modulated signal and analyzing the returned signal to determine range, velocity, and other characteristics of the target. Unlike pulsed radar, FMCW radar continuously transmits and receives, making it suitable for high-precision, short-range measurements.

The radar transmits a linearly frequency-modulated (LFM) signal (a chirp). The received signal, which is a delayed version of the transmitted signal due to reflection from a target, is then mixed with the simultaneously transmitted signal. This mixing process, known as de-chirping, produces an intermediate frequency (IF) signal at a beat frequency ($\boldsymbol{f_b}$). This beat frequency is directly proportional to the distance to the target.

The relationship between range (R) and beat frequency (f_b) in a vacuum is given by:

$$\left[R = \frac{f_b \cdot c \cdot T_{chirp}}{2 \cdot BW}\right]$$

2.1 Simulation using MATLAB

This MATLAB script simulates the electromagnetic interaction of a Frequency-Modulated Continuous Wave (FMCW) radar signal with a multilayer structure consisting of air, diesel, contaminated water, and a metallic base (steel). The core objective is to evaluate how varying levels of water contamination within the diesel layer influence the radar's reflected signal—specifically analyzing the S11 reflection coefficient and its phase behavior over a defined frequency spectrum. The simulation supports both parallel and perpendicular polarizations of the incident wave and offers user-defined inputs for key parameters, such as incidence angle, layer thicknesses, and frequency range. This model is particularly suited for applications involving non-invasive radar-based level measurement in storage tanks (e.g., diesel tanks prone to water contamination) and for assessing dielectric properties of layered materials in industrial environments.

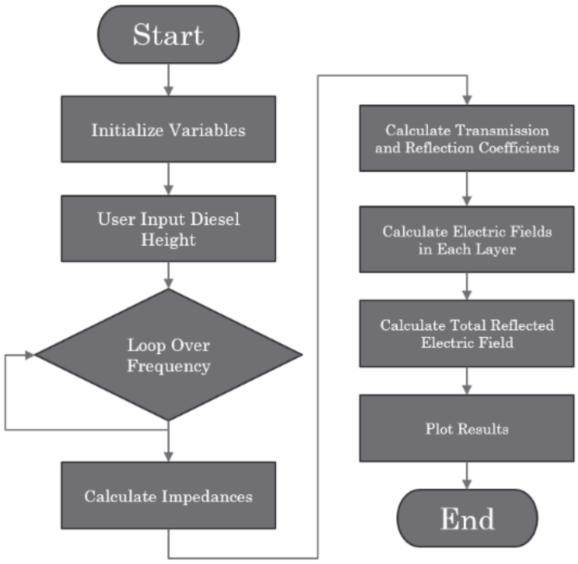

Figure 0-1: Flowchart showing the MATLAB code procedure

Propagation Constant:

$$\gamma = \sqrt{\left(i\omega\mu_0\mu_r(\sigma + i\omega\varepsilon_r\varepsilon_0)\right)}$$

Intrinsic Impedance:

$$\eta = \sqrt{\left((i\omega\mu_0\mu_r)/(\sigma + i\omega\varepsilon_r\varepsilon_0)\right)}$$

Snell's Law:

$$\theta_t = \arcsin\left(\sqrt{(\varepsilon_i/\varepsilon_t)\backslash\text{cdotsin}}(\theta_i)\right)$$

Step-by-Step Approach

User Inputs: Frequency range, diesel height, water contamination step, polarization type, and angle of incidence.

Initialization: Define physical constants and construct frequency sweep vector.

Material Properties Setup: Assign dielectric properties to air, diesel, water, and steel.

Loop Over Water Depths: Calculate propagation constants, impedance, angles, and electric fields. Derive total reflected field and S11.

Post-Processing: Convert the phase of the reflected signal to degrees and plot the phase vs frequency for varying contamination levels.

4. Applied Example

Inputs:
Minimum Frequency: 3 GHz

Maximum Frequency: 6 GHz

Diesel Height: 100 cm

Water Contamination Step: 2 mm

Polarization: Parallel

Frequency and Angular Frequency

$$f = \text{linspace}(6\,\text{GHz}, 10\,\text{GHz}, N)$$

Angular frequency:

$$\omega = 2\pi f$$

Relative Permittivity for Each Medium

Air:

$$\varepsilon_r^{(air)} = 1$$

Diesel:

$$\varepsilon_r^{(diesel)} = 2.1 - 0.001i$$

Water:

$$\varepsilon_r^{(water)} = 78 - 10i$$

Steel (conductor, modeled with complex permittivity):

$$\varepsilon_r^{(steel)} = -1000 - 1000i$$

Absolute Permittivity

$$\varepsilon = \varepsilon_r \cdot \varepsilon_0$$

Where:

$$\varepsilon_0 = 8.854 \times 10^{-12}\ \text{F/m}$$

Wave Number

$$k = \omega\sqrt{\mu_0 \varepsilon}$$

Where:

$$\mu_0 = 4\pi \times 10^{-7}\ \text{H/m}$$

Reflection Coefficients Between Layers

At the air–diesel interface:

$$r_{12} = \frac{k_1 - k_2}{k_1 + k_2}$$

At the diesel–water interface:

$$r_{23} = \frac{k_2 - k_3}{k_2 + k_3}$$

At the water–steel interface:

$$r_{34} = \frac{k_3 - k_4}{k_3 + k_4}$$

2.2 Phase Shift in Each Layer

For layer thickness and wave number:

$$\phi = 2\,k\,d$$

Recursive Reflection Coefficient Calculation

Total reflection at water–steel interface:

$$r_{34}^{total} = r_{34}$$

Total reflection at diesel–water interface:

$$r_{23}^{total} = \frac{r_{23} + r_{34}^{total} e^{-2ik_3 d_3}}{1 + r_{23} r_{34}^{total} e^{-2ik_3 d_3}}$$

Total reflection at air–diesel interface (final S11):

$$\Gamma = r_{12}^{total} = \frac{r_{12} + r_{23}^{total} e^{-2ik_2 d_2}}{1 + r_{12} r_{23}^{total} e^{-2ik_2 d_2}}$$

Return Loss / Reflection Magnitude in dB

$$|\Gamma|_{dB} = 20\log_{10}|\Gamma|$$

2.3 Simulation using CST Software

To visualize the theoretical framework, a 3D electromagnetic simulation was conducted using CST Studio. The setup modeled a tank equipped with both transmitting and receiving antennas positioned above it. Digital representations of diesel and water layers were constructed, with material properties assigned based on estimated or database-sourced permittivity values.

The simulation mesh targeted a cross-sectional view of the tank and included discrete field probes to measure electric field intensity at multiple depths. A frequency-swept sinusoidal signal was used to emulate the FMCW radar waveform. The simulation results revealed distinct reflection patterns at the interfaces between different liquid layers, validating the theoretical model and offering strong support for subsequent experimental work.

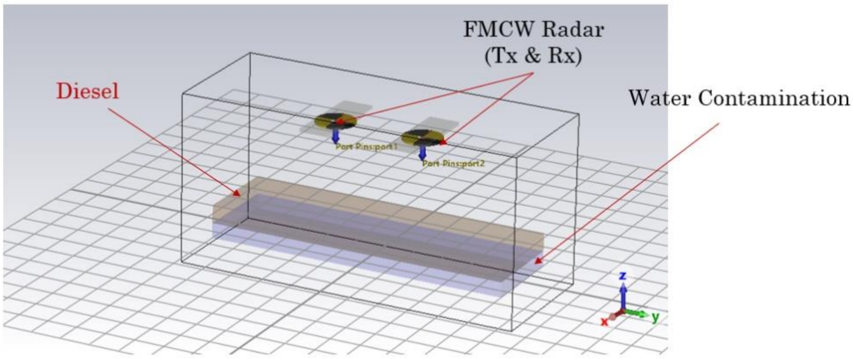

Figure 0-2: *Simulation Model in CST Studio*

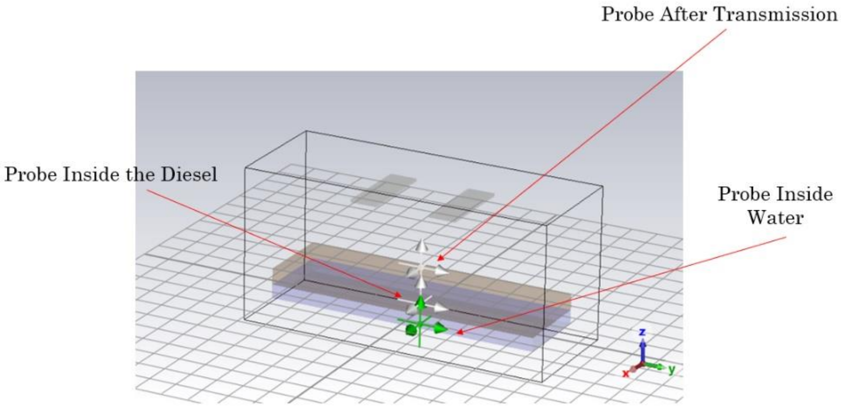

Figure 0-3: *Electric Fields Probes inside liquids layers*

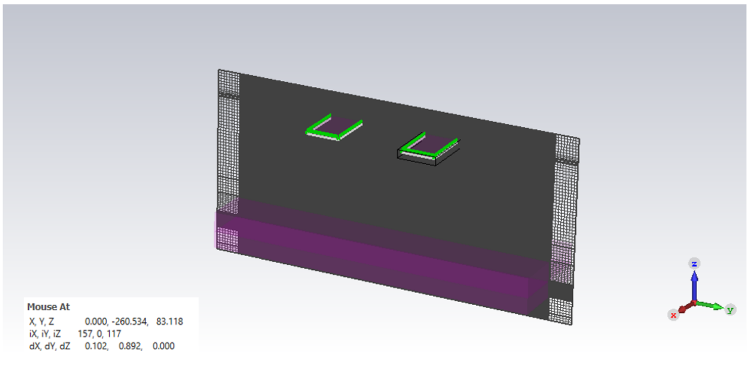

Figure 0-4: *Meshing for Tank section*

3. Results

3.1 MATLAB Simulation Findings

The simulation results revealed distinct phase shifts in the reflected radar signal corresponding to rising water levels beneath the diesel layer. As water contamination was increased in millimeter-scale increments, a consistent relationship emerged between the depth of the water and the phase of the reflected signal.

Electric field plots—mapped against both depth and time—showed increasing signal distortion as water content rose, indicating more complex interactions at the fluid interfaces. These results not only confirmed the accuracy of the theoretical model but also established a reliable reference for comparison with CST simulations and experimental measurements.

3.2 CST Software Modeling Findings

The CST simulation results supported the findings obtained from the MATLAB model. Field probes placed at various material boundaries recorded noticeable changes in electric field strength, particularly at the interface between diesel and water. In the simulation outputs, the black line highlighted the electric field magnitude within the water layer, clearly indicating its unique response due to its higher permittivity.

Additional simulations were conducted using mineral oil, user-defined dielectric properties, and air to approximate the behavior of the layered system. Although these materials did not perfectly replicate real-world conditions, they effectively demonstrated how electromagnetic waves interacted with different media. The results showed how each interface influenced the waveform, providing insight into the distinct electromagnetic signatures generated by each layer. These findings validate the system's ability to detect and differentiate between multiple fluid layers based on their dielectric characteristics.

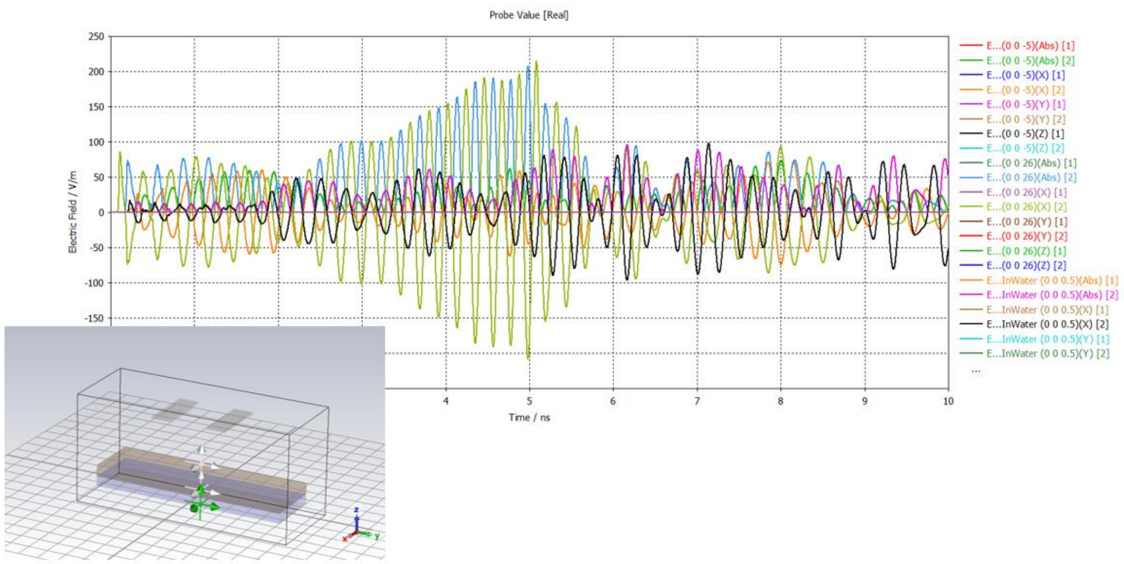

Figure 0-1: *Probe values for Electric Field Transmission and Reflections*

4. Conclusions

This research successfully demonstrates the feasibility of using Frequency-Modulated Continuous Wave (FMCW) radar for detecting water contamination in diesel storage tanks with high precision. Through a combination of electromagnetic modeling, CST-based simulations, and MATLAB signal processing, the system proved capable of distinguishing between diesel and water layers by leveraging differences in dielectric properties and signal attenuation. Small volumes of water—introduced in millimeter-scale increments—were reliably detected by analyzing the phase and amplitude of reflected radar signals.

The multi-layer simulation model, representing air, diesel, water, and tank wall, closely mimicked real-world conditions, while advanced signal processing techniques such as phase unwrapping and matched filtering enhanced detection sensitivity. The system's ability to operate at high frequencies ensures high resolution and minimal signal interference, making it well-suited for industrial fuel management where accuracy and reliability are critical.

This radar-based method offers a non-contact, real-time alternative to traditional techniques, which are often invasive or prone to error. It is robust against tank geometry variations, surface disturbances, and environmental noise. By detecting even thin water layers before they accumulate and cause damage, the system helps mitigate corrosion, microbial growth, and mechanical failure, contributing to improved operational safety and reduced maintenance costs.

In conclusion, this study provides a strong foundation for the deployment of FMCW radar in fuel quality monitoring, offering a scalable, cost-effective solution for both stationery and mobile tank systems. Future enhancements may include integrating machine learning for automated detection and expanding the system to monitor various fluid combinations under different environmental conditions.

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