A novel approach to monitoring levels in naval shipboard seawater ballasted fuel oil storage tanks has been developed at the David Taylor Naval Ship Research and Development Center of Annapolis, Maryland. The Electromagnetic Level Indicator (EMLI) uses the pulsing and high frequency sampling techniques of Time Domain Reflectometry (TDR) to interrogate a single no moving parts probe to accurately measure the height of seawater, fuel oil and air columns in the ballasted fuel oil tanks.

In addition, the EMLI can be used to measure a broad range of single or multiple levels of immiscible fluids and flowing solids. The system also offers the potential of content identification, detection and measure of emulsion layers, and pollution control. Final system configuration is expected to be simple and automatic, requiring less maintenance than tank level indicators currently in use.

This paper is intended to provide a general understanding of the theory of operation, describe the system components, present preliminary test and performance data, and propose applications for the EMLI.

**Theory of Operation**

Distributed circuit theory states that if a pulse is launched onto a transmission line with segments of differing characteristic impedances, pulse reflections will occur at each impedance mismatch. The amount of reflection at each mismatch can be related to the initial pulse amplitude by a series of reflection coefficients. The velocity of propagation of the pulse along the transmission line is primarily dependent upon the dielectric constant of the material separating the line's conductors. TDR using both pulse reflection and velocity of propagation measurements is useful in accurately locating transmission line faults (impedance mismatches).

The theory of TDR has been applied to tank level measurements in the following manner. A probe, electrically resembling a coaxial transmission line, allows the tank's contents to flow freely between the inner and outer conductors and act as the line dielectric. If a TDR unit is electrically connected to such a probe immersed in a tank, pulse reflections occurring at fluid interfaces and velocity of propagation of the pulses along the probe can be measured. By relating pulse time of transit and reflection amplitude information, the length and location of a fluid along the probe can be determined.

The equation used to solve for fluid level measurement is derived here for the specific case of a tank containing seawater, oil and air. Assume that the TDR is electrically connected to the probe at the tank top and that the TDR output impedance, cable impedance and probe in air impedance are matched such that no pulse reflections occur before the air-oil interface. Pulse reflections occur at the air-oil and oil-seawater interfaces. (Fig. 1)
since $\varepsilon_{\text{air}} = 1.3$. Substituting this into equation (1) yields a relationship between the waveform voltages for air and oil to the dielectric constant of the oil.

The time of transit of the pulse through a fluid, fluid, $f$, can be described by the following:

$$T_f = \frac{D_f \sqrt{\varepsilon_f}}{c}$$  \hspace{1cm} (5)

where $D_f$ is the distance the pulse travels through the fluid and $c$ is the speed of light in free space. Note that the voltage and time of transit equations can each be written in terms of the fluid dielectric constant and then equated. This yields a solution for the length of a fluid along the probe. For the case of air and oil, the length of each is found to be:

$$D_{\text{air}} = c \cdot T_{\text{air}}$$

and

$$D_{\text{oil}} = c \cdot T_{\text{oil}} \cdot \frac{\varepsilon_{\text{oil}}}{V_{\text{oil}}}$$  \hspace{1cm} (6)

Equation (7) determines the length of the oil along the probe solely from voltage and timing information provided by the TDR, eliminating the dielectric variation effects.

In a similar fashion, the length of seawater along the probe could be calculated with the exception that $Z_{\text{seawater}}$ cannot be modeled as in equation (3) due to other electrical properties exhibited by seawater. However, knowledge of the overall length of the probe, its length in air and length in oil makes independent calculation of seawater length redundant.

**System Description**

The EMLI system's probe consists of two conductors assembled to act as a high frequency transmission line electrically connected to the TDR module output. To insure proper system operation, the probe must exhibit good electrical properties and be able to withstand a corrosive environment. The major design guidelines are as follows:

(i) constant probe impedance in air, matched to the cable and TDR output impedance

(ii) conductor spacing sufficient to allow tank contents to flow between them and to minimize "coating-action."*

(iii) low loss, low VSWR cable-to-probe connections at operating frequencies.

(iv) corrosion resistant materials and rugged construction.

Tests to date have yielded the basic design of a pipe or tube mounted within a half-pipe (Fig. 3).
The connection of the probe to the cable is made outside of the tank to eliminate cable/connection deterioration due to exposure to tank contents. The connection is sealed and hardened to prevent environmental degradation. The probe is terminated in an electrical short at the tank bottom for a positive end-of-probe indication.

The materials selected for the probe conductors are resistant to pit and crevice corrosion, and galvanic corrosion is prevented by electrically isolating the probes from the tank walls.

The probe is designed to be easily assembled in sections and secured within the tank. Since there are no moving parts, the probe requires no servicing under normal operating conditions.

TDR Pulsing and Sampling Circuits

The TDR pulsing and sampling circuits launch the electromagnetic wave along the cable and probe, and sample the returning signal.

A voltage step having a very fast rise time, $<150$ picoseconds, is generated by a tunnel diode. This step creates a wavefront propagating along a stripline attached to the external cable connection which, in turn, is connected to the probe. At the fluid interfaces, impedance mismatches occur, generating a reflection. The returning reflections are detected on the stripline by a pair of sampling diodes which are strobed on for 100 picoseconds at discrete time intervals to fully sample the returning pulses. An equivalent time sampling circuit is used to view the fast repetitive signal. This circuit samples at 25 picosecond intervals and holds the voltage level for approximately 25 microseconds before the next point is sampled. Thus, the fast analog signal can be readily converted to digital signal for signal processing.

The Signal Processor

The signal processor consists of an A/D converter, a buffer memory, a microprocessor, and output circuitry. The signal from the TDR unit is converted to digital data and stored in a buffer. The microprocessor averages several waveforms and analyzes the data to solve for the voltage amplitudes and the propagation times. The data is used to calculate the height of each fluid (see equations in Theory of Operation). The output circuitry transfers the height information to the display.

Display

The display consists of circuitry to accept the digital data from the signal processor, fluid level to volume converters (look-up tables in memory) and an analog bar graph and digital readout display. The digital signal containing the fluid level information is compared to the look-up table to convert to volume. This volume information is displayed by the bar graph in a percent full mode. The digital readout provides the number of gallons of fuel oil present to three and one-half digit accuracy.

General Performance

The EMLI system was tested with several experimental probe designs using both commercially available TDR's and a prototype thick-film hybrid microelectronic TDR. The probes were tested under static conditions in a 3 meter tank containing fuel oil (MIL-F-16884 DPM) and artificial seawater. The probes were also tested under dynamic conditions which included severe mixing of the fuel oil and seawater columns.

Additional data was collected to measure system accuracy over a fuel-oil temperature range of $-5^\circ$ to $45^\circ$C and distilled water from $0^\circ$ to $80^\circ$C. Level measurements were made with several other fluids with dielectric constants ranging from 4 to 80. Direct comparisons of the prototype, thick-film microelectronic TDR module were made against two commercial TDR's.

The results of the testing can be summarized as follows:

(i) Matched system impedances resulted in better resolution than mismatched systems.

(ii) Linearity was typically better than 0.7 cm over a 3 meter span.

(iii) System resolution is at least 0.7 cm and is typically better than 0.5 cm (over a 3 meter span).

(iv) The EMLI system is capable of resolving an oil column and a seawater column in the presence of interface emulsion or mixing.

(v) Dielectric variations, fluid type, a broad temperature range, and contamination can be accounted for, and do not result in a loss of system accuracy.

(vi) System resolution and linearity using the prototype TDR module compare favorably with the commercially available TDR units used in the testing.

Applications

Based upon test data, the EMLI system will be useful for a broad range of tank level measurements. The sensor is able to tolerate fluid coatings without loss of accuracy and can be used to measure the level of viscous fluids. Limited fluid interface agitation and foaming are handled by signal averaging and do not present a problem in level measurements. The system can be used to measure fluid levels in both single and multi-content tanks and is useful as either a continuous or point level sensor.

Other EMLI application areas include:

- Pollution control - due to the nature of the TDR output signal, the presence of a fuel oil-seawater emulsion can be detected.
- Content identification - the dielectric constants of the fluids in a tank can be calculated by the system to identify the fluids for proper display or inventory.
- Energy usage - accurate measurements of the fuel in tanks provides a method to establish fuel oil consumption rates and predict overall energy efficiency.
References


