NOVEL METHODS OF MEASURING IMPURITY LEVELS IN LIQUID TANKS

Matthias Weiß, Reinhard Knöchel

Lehrstuhl für Hochfrequenztechnik,
Technische Fakultät der Christian–Albrechts–Universität zu Kiel,
Kaiserstr. 2, D-24143 Kiel, Germany

ABSTRACT

A microwave multi level gauging system employing a FSCW radar measurement technique is described. Conventional FMCW radar technique is normally employed to find only the level of the liquid surface in storage tanks. The system described here also detects a second level, caused for example by an impurity such as water in a petrol tank. For estimating the time delay and amplitude of each reflection from each scatterer an optimal signal processing algorithm is derived, based on a reference model. To determine the physical height of the impurity level, in for example petrol tanks, the dielectric constant of the petrol must be known. A novel algorithm is derived for estimating this from the same measurement. Measurement uncertainties of ± 0.2 mm have been achieved for the multi level range detection, performed in the frequency range from 1.5 to 3.5 GHz. From this measured data the error of the calculated dielectric constants was about to 1 %. This yields an accuracy for the petrol height of 0.5 %.

INTRODUCTION

Measuring and controlling liquid levels contained in storage tanks and processing vessels is important in many industrial processes. In the case of storage tanks impurities or contaminants can settle for example water and sediments in the mineral oil industries. To prevent these impurities reaching the next process step the monitoring of this level is essential. Until now a scheduled maintenance of the storage tanks was carried out. This scheduled maintenance could be replaced by on-call maintenance if the contaminant level was well known.

In this paper we describe a microwave FSCW (**F**requency **S**tep **C**ontinuies **W**ave) radar system which can monitor the liquid surface and the impurity level. To extract the time-delays τ_1 (liquid surface) and $\tau_2 = \tau_1 + \Delta\tau$ (impurity level) accurately from the measured data a reference model algorithm is used [3]. To calculate from these time-delays the physical height of the impurity level the dielectric constant of the top liquid must be known

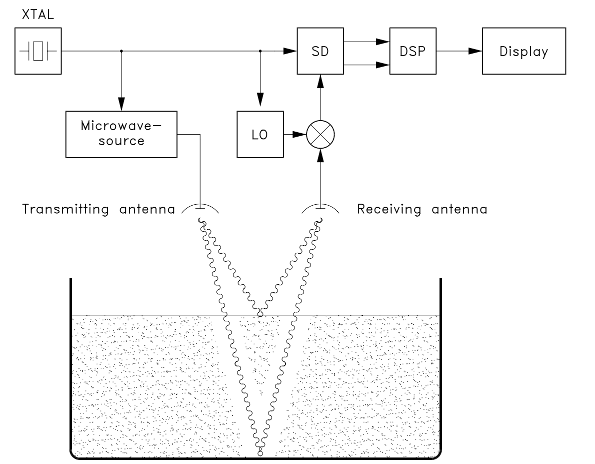

Fig. 1. Schematic diagram of an FSCW radar measuring a liquid gauge in a storage tank.

$l_{impurity} = l_{tank} - (\tau_1 + \Delta\tau\sqrt{\epsilon_r})\, c_0$. A novel algorithm is derived to determine this unknown constant from the same measurement.

THE REFERENCE MODEL

An FSCW system transmits a sequence of sinusoids at different frequencies and measures the steady-state amplitude and phase shift induced by the radar channel. One significant benefit of performing the measurements at discrete frequencies is the ease with which digital signal processing technique may be applied to the data. To maximize the range resolution achievable from an FSCW radar a reference model technique is applied. By this technique a signal processing computer produces a synthesized data set, at the frequencies at which the measurements were taken, and compares it to the physical measurements. The computerized data are based on an underlying physical model of the transfer function of the radar channel.

Finally the algorithm has to minimize the difference between both the measured and synthesized data. After minimization is performed the parameters of the reference model represent the ranging results. The best results where achieved with least squares estimation.

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This algorithm is derived for one reflection in the radar channel. On the assumption that the amplitude of the reflection coefficient is real, which is justified for liquids where $\epsilon_r' \gg \epsilon_r''$, the formulation of the reference model is

$$H_m(A,\tau) \;=\; A\,e^{-j\omega_m\tau} \;=\; A\,e^{-j(\omega_0 + m\,\Delta\omega)\tau} \quad . \tag{1}$$

with A the reflection coefficient of the discontinuity and ω_m the measured frequency which is in the range from the startfrequency ω_0 to $\omega_0 + m\,\Delta\omega$ ($m = 0 ... \mathrm{N}-1$). The distance l of the reflection in the reference model leads to the time delay $\tau = 2\,l/c$.

The general least squares optimization problem becomes finding the amplitude A and delay τ in the reference model that minimize

$$FF(A,\tau) \;=\; \sum_{m=0}^{\mathrm{N}-1} \Big| M_m \;-\; H_m(A,\tau) \Big|^2 \tag{2}$$

where the summation index m ranges over the N measured data pairs M_m. This error function $FF(A,\tau)$ can be analytically minimized by the amplitude A. This yields

$$FF(\tau) \;=\; E_M \;-\; \frac{\Big(\Re\mathcal{F}_{(\tau)}\{\Re M_m\} \;-\; \Im\mathcal{F}_{(\tau)}\{\Im M_m\}\Big)^2}{\mathrm{N}} \tag{3}$$

where E_M denotes the energy of the measured signal M_m and $\mathcal{F}_{(\tau)}\{...\}$ represents the Fourier transform operator, evaluated at the time τ. The amplitude of the reflected pulse can be determined as

$$A \;=\; \frac{\Re\mathcal{F}_{(\tau)}\{\Re M_m\}}{\mathrm{N}} \;-\; \frac{\Im\mathcal{F}_{(\tau)}\{\Im M_m\}}{\mathrm{N}} \tag{4}$$

DETERMINING THE DIELECTRIC CONSTANT FROM THE MEASURED REFLECTION COEFFICIENTS

In this section we presents a novel method for determining the dielectric constant of a low loss liquid. On condition that the measured fluid have no dispersion ($\partial\epsilon_r/\partial f \approx 0$) it is possible to determine accurately in the time domain the time delay and amplitude for the reflected pulse from each scatterer (interface). To derive the algorithm a dispersion free probe is used. This is not however a restriction of the algorithm. With modification of the reflection model it is also possible to use a waveguide as a probe. The advantages of this method are that the attenuation characteristics of the probe need not be known and no other measurement is required.

Consider the coaxial sensor, which is terminated by an absorber, and its theoretical bounce diagram

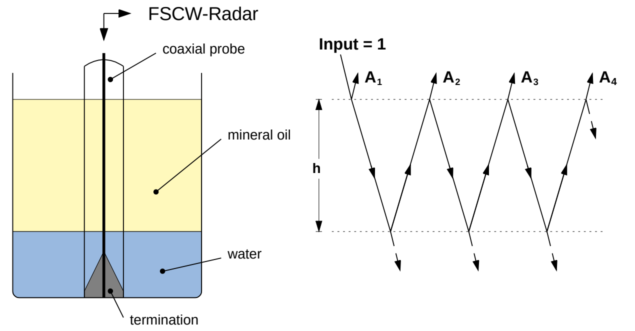

Fig. 2. Schematic measurement setup with a coaxial line ending with an absorber termination and the bouncing diagram for a unit impulse stimulus with the resulting multiple reflections.

as shown in figure 2. The sensor stands in a storage tank filled with diesel and water, which is an impurity of mineral oil and is of course denser.

If Γ_1 denotes the reflection coefficient from the liquid surface and Γ_2 from the diesel/water interface, then we can write for the first few reflection amplitudes the following relationships

$$A_1 \;=\; \Gamma_1 \cdot \exp\{-\alpha_1\,\tau_1\} \tag{5}$$

$$A_2 \;=\; (1+\Gamma_1)\,\Gamma_2\,(1-\Gamma_1) \cdot \exp\{-(\alpha_1\tau_1 + \alpha_2\,\Delta\tau)\} \tag{6}$$

The general expression for the nth reflection where $n > 2$ is given by

$$A_n \;=\; A_{n-1}(-\Gamma_1)\Gamma_2\exp(-\alpha_2\Delta\tau) \quad .$$

α_1 denotes the loss factor of the air filled sensor and α_2 of the diesel filled part. The time delay, caused by the additional pathlength of the electromagnetic wave between the diesel surface and the diesel/water interface, is indicated by $\Delta\tau$.

To eliminate the effect of the air filled part of the sensor on the reflection amplitudes we take the ratio of the first two reflection amplitudes and of the third and second one. This results in the following two equations:

$$\frac{A_2}{A_1} \;=\; \frac{(1+\Gamma_1)\,\Gamma_2\,(1-\Gamma_1)}{\Gamma_1}\,e^{-\alpha_2\Delta\tau} \tag{7}$$

$$\frac{A_3}{A_2} \;=\; \frac{\Gamma_2^2(-\Gamma_1)(1+\Gamma_1)(1-\Gamma_1)}{(1+\Gamma_1)\,\Gamma_2\,(1-\Gamma_1)}\,e^{-\alpha_2\Delta\tau} \;=\; -\,\Gamma_2\,\Gamma_1\,e^{-\alpha_2\Delta\tau} \tag{8}$$

Dividing equation (7) by (8) provides

$$\Rightarrow \quad \nu \;=\; \frac{A_2^2}{A_1\,A_3} \;=\; \frac{\Gamma_1^2 - 1}{\Gamma_1^2} \quad . \tag{9}$$

Because this term ν depends only on the surface reflection coefficient Γ_1 and is not influenced by the sensor attenuation it can be used to determine the dielectric constant. Taking into consideration the fact that

$$\Gamma_1 = \frac{Z - Z_0}{Z + Z_0} = \frac{1 - \sqrt{\epsilon_r}}{1 + \sqrt{\epsilon_r}} \qquad (10)$$

equation (9) can be transformed to

$$\sqrt{\epsilon_r} = \frac{2\nu - 4}{2\nu} \pm \sqrt{\left(\frac{2\nu - 4}{2\nu}\right)^2 - 1} \quad .(11)$$

Only the plus sign in eqn. (11) gives reasonable results. With this the physical diesel level is obtained from the time delay by

$$l_{\text{diesel}} = \frac{\Delta\tau\, c}{2\sqrt{\epsilon_r}} \quad . \qquad (12)$$

and the depth of the impurity

$$l_{impurity} = l_{tank} - (\tau_1 + \Delta\tau\sqrt{\epsilon_r})\, c \qquad (13)$$

EXPERIMENTAL RESULTS

Figure 3 shows the experimental setup. The coaxial sensor, which has a length of 850 mm, stands in a glass cylinder filled with diesel. To verify the algorithm for determining the dielectric constant from a reflection measurement the sensor ends with a short. This short simulates an impurity interface with an ideal reflection coefficient. The FSCW measurements was carried out by the means of a HP8510C network analyzer. The fluid level was changed in 1 mm steps. In this way, measurements were taken in the range of 70 to 450 mm above the end of the probe.

In figure 4 a comparison of two range algorithms is shown for the strong reflection from the short. The dotted line was processed by the conventional technique, i.e. performing the inverse FT and determining the time domain delay. The solid line is the result of the comparison between the measured data and the reference model. Its variation lies within limits of approximately ± 0.1 mm.

This good result for the range detection of the short also was obtained for the liquid surface. This is shown in figure 5. The range error of the inverse FT is about two orders of magnitude higher (± 20 mm) than that of the reference model.

After determining the time delays for the surface and the short, it is possible to calculate the amplitudes for the first three reflected pulses. With these amplitudes and equation (11) the dielectric constant of the diesel can be calculated. As shown in figure 6, the uncertainty in ϵ_r is about ± 1 %.

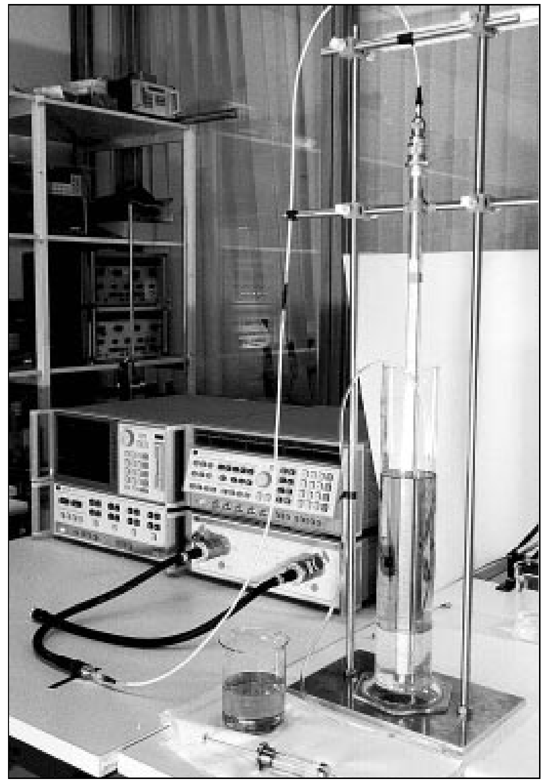

Fig. 3. Experimental setup

With this dielectric constant it is possible to calculate the physical height of the impurity level. This is done with

$$l_{impurity} = (l_{tank} - l_{surface})/\sqrt{\epsilon_r} \qquad (14)$$

Figure 7 shows the resulting error of the impurity level which has an uncertainly of about ± 2 mm. This error is only caused by the variation of the determined ϵ_r (see fig. 6). With an uncertainty of 1% in determining ϵ_r with the novel algorithm an error of about 1.5 cm will occur for the impurity depth in a tank of height 3 meters.

CONCLUSIONS

A microwave multilevel gauging system for industrial applications requiring sub-millimeter accuracy for the surface has been described. With this gauging system it is also possible to detect a contaminant level and determine its physical height.

The algorithm used, the reference model, for determining the time-delays of the different levels is based on minimizing the least squares estimation of measured reflection data and those produced by a

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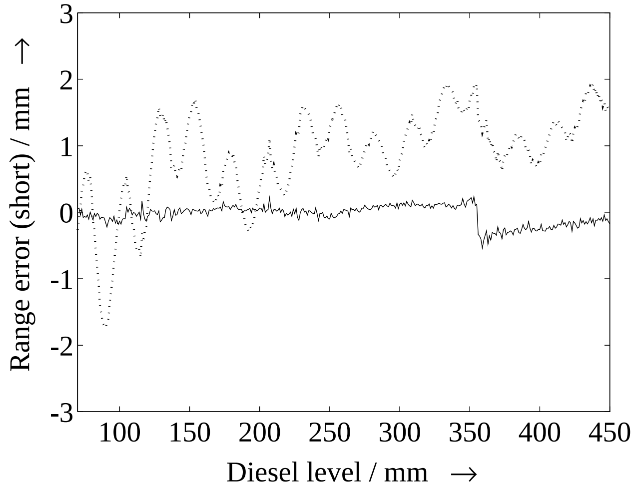

Fig. 4. Comparison of two algorithm for the distance measurement. The dotted line shows the result of the IFT and the thin line of the reference model ($\epsilon_r = 2,15$).

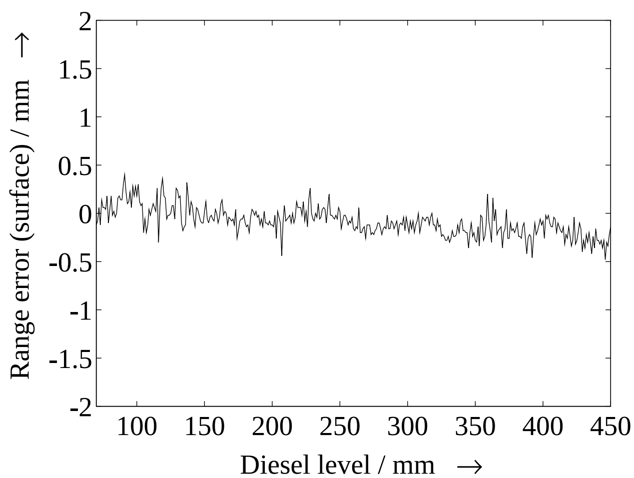

Fig. 5. Range error of the diesel surface achieved by the reference model.

reference model that assumes the echoes from the radar channel are pulses in the time domain. The measurement was carried out with a shorted coaxial sensor by an HP8510C network analyzer. The reference model was clearly able to resolve the time delays of the first two reflections with high accuracy.

To calculate the physical liquid levels from the time delays the dielectric constant of the top fluid is needed. A novel algorithm for determining the required dielectric constant from the reflection measurement data has been devised. The advantage of this algorithm is that for determining the dielectric constant no other measurement or assumption is needed. This feature could be important in industrial applications where an impurity level in a tank exists. For example in the petrochemical industries water is always present. With an accurate knowledge of the impurity level regular scheduled maintenance can be replaced by maintenance as required.

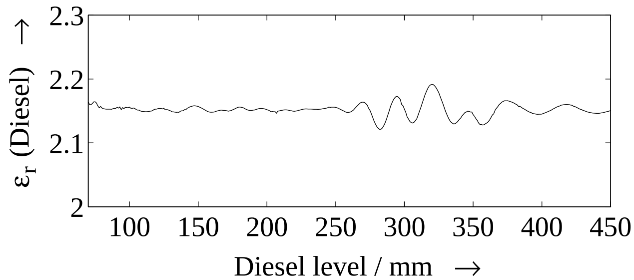

Fig. 6. Dielectric constant of diesel calculated from the amplitudes of the first three reflection impulses.

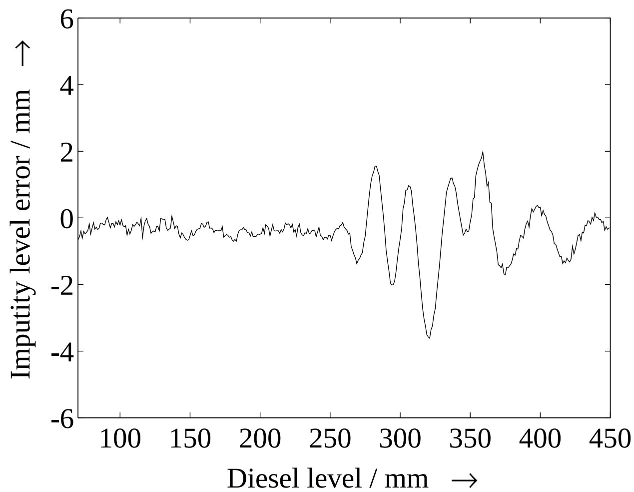

Fig. 7. Calculated level error for the impurity.

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