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Equivalent Circuit Model and Evaluation of Inductive Conductivity Sensors

Michael Vogt[1], *Malte Mallach*[2], *Theresia Lange*[2], *Jan Förster*[2]
[1] *KROHNE Messtechnik GmbH, Duisburg, Germany,*
[2] *KROHNE Innovation GmbH, Duisburg, Germany*
m.vogt@krohne.com

Summary:
Inductive sensors allow for contactless measurement of the electrical conductivity of liquids. A first magnetic coil is used for inducing an eddy current into the liquid, and this current is measured with a second coil. In this contribution, an equivalent circuit model is presented, including also a parasitic direct coupling and the liquid's electrical permittivity. It will be shown analytically and with measurement results that the real part of the ratio of the measurement voltages has to be evaluated and that a trans-impedance amplifier with a small input-impedance has to be used for accurate measurements.

Keywords: Measurement sensor, electrical conductivity, liquid, coil, eddy current

Introduction

The measurement of the *electrical conductivity* of liquids is an important task in many industrial processes [1]. In the case of *aggressive* liquids (acids, bases, etc.), preferably *inductive* conductivity sensors are used, because no electrodes are in contact with the liquid [2].

Inductive Conductivity Sensors

Fig. 1 shows the setup of an inductive conductivity sensor, which is *immersed* into the liquid:

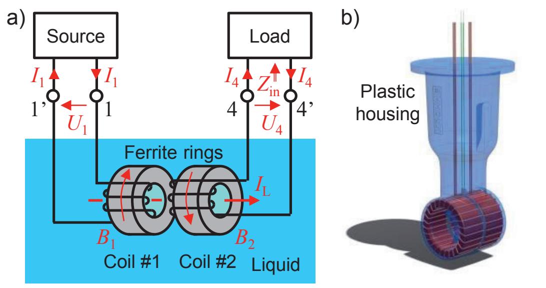

Fig. 1. Inductive conductivity sensor: a) Principle and connection setup, b) sensor design with housing.

The first toroidal coil #1 is driven by a sinusoidal voltage U_1 at an angular frequency $\omega = 2\pi \cdot f$ (frequency f), resulting in a current I_1 and a magnetic inductance B_1. The latter induces an *eddy current* I_L into the *liquid*, and this current is flowing through the inner hole of the sensor housing and its surrounding. The eddy current I_L causes a magnetic inductance B_2 in the second toroidal coil #2, which induces a voltage U_4. The coil #2 is loaded with a *trans-impedance amplifier* (with an input-impedance Z_{in}), resulting in a current $I_4 = U_4 / Z_{in}$.

Equivalent Circuit Network

In Fig. 2, an equivalent circuit network (ECN) of the sensor in Fig. 1 is shown:

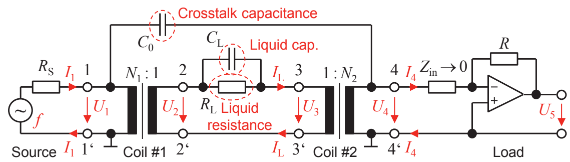

Fig. 2. Inductive conductivity sensor: Equivalent circuit network.

The *electrical conductivity* σ_L of the *liquid*, which is to be measured here, is included in the *conductance* $G_L = 1 / R_L = \sigma_L / k_{cell}$ (*resistance* R_L) of the liquid, with the so-called '*cell constant*' k_{cell} of the sensor (depending on its geometry). The two coils (*numbers of windings* N_1 and N_2, *inductances* L_{11} and L_{44}) together with the current loop through the conductive liquid are each represented by an ideal, lossless transformer [2]. Furthermore, the ECN in Fig. 2 also includes a *parasitic crosstalk capacitance* C_0 (direct *coupling* between the two coils), and the *capacitance* $C_L = \varepsilon_L / k_{cell}$ of the *liquid* (permittivity $\varepsilon_L = \varepsilon_{r,L} \cdot \varepsilon_0$, relative permittivity $\varepsilon_{r,L}$, vacuum permittivity ε_0). Based on Fig. 2, the following ratio H_m between the *output voltage* $U_5 = -R \cdot I_4$ and the *excitation voltage* U_1 is given:

$$H_m = \frac{U_5}{U_1} = -R \cdot \frac{\frac{N_2}{N_1} + j\omega \cdot R_L \cdot \left(N_2^2 \cdot C_0 + \frac{N_2}{N_1} \cdot C_L\right)}{Z_{in} \cdot (1 + j\omega \cdot R_L \cdot C_L) + R_L \cdot N_2^2 \cdot (1 + j\omega \cdot Z_{in} \cdot C_0 + Z_{in} / (j\omega \cdot L_{44}))} \qquad (1)$$

The concept of the sensor is to measure the voltages U_5 and U_1 and to assess their ratio H_m in order to estimate the resistance R_L of the *liquid* (and so the conductivity σ_L) by means of (1). However, the parameters L_{44}, C_0, and also Z_{in} can significantly *change* over different samples of the same type of sensor, and also over temperature, aging, etc. For this reason, these parameters and also the *unknown* C_L have to be *eliminated* from the measurement (compare [1]). This can be achieved by using a *trans-impedance amplifier* with a sufficiently *small* input-impedance Z_{in}, a sufficiently *large* angular frequency ω, and a *large* inductance L_{44} giving $|Z_{in}| << \omega \cdot L_{44}$, and $|Z_{in}| << 1/(\omega \cdot C_0)$, and $|Z_{in}| << R_L \cdot N_2^2 / |1+j\omega \cdot R_L \cdot C_L|$. Under these conditions, H_m is given as follows, see (1):

$$H_m = \frac{U_5}{U_1} = -R \cdot \left(\frac{1}{N_1 \cdot N_2 \cdot R_L} + j\omega \cdot (C_0 + \frac{C_L}{N_1 \cdot N_2})\right) \quad (2)$$

The result in (2) shows that R_L is now directly accessible from the *real part* $\mathrm{Re}(H_m)$ of the voltage ratio H_m, scaled by the *numbers of windings* N_1 and N_2 of the two coils:

$$\mathrm{Re}(H_m) = \mathrm{Re}\left(\frac{U_5}{U_1}\right) = -\frac{1}{N_1 \cdot N_2} \cdot \frac{R}{R_L} \quad (3)$$

Because of this scaling in (3), *inductive* sensors are preferably used for liquids with *large* conductivities σ_L (i.e. with *small* resistances R_L). In contrast, conductivity sensors with *Galvanic coupling* are to be preferred for liquids with *small* conductivities [1].

Experimental Evaluation

Measurements have been performed with a sensor (with $k_{cell} = 6.25\,\mathrm{cm}^{-1}$, $N_1 = N_2 = 25$, $L_{11} = L_{44} = 12\,\mathrm{mH}$, $f = 2.5\,\mathrm{kHz}$, $R = 1\,\mathrm{k\Omega}$) in order to verify the findings above and to evaluate the achievable measurement accuracy and range. The voltage ratio H_m has been directly measured with a calibrated *vector network analyzer* (model Bode 100; OMICRON electronics GmbH, Klaus, Austria). For measurements under *known* and *well-defined* conditions, the liquid has been replaced by a *metallic wire* (as current loop) through the inner hole of the sensor. The loop has been loaded with a changing *lumped* resistance $R_L = 12\,\Omega\,..\,220\,\mathrm{k\Omega}$. For each different R_L, an according *nominal given* conductivity $\sigma_L = k_{cell} / R_L$ has been calculated. In Fig. 3, the *measured nominal* conductivity σ_L over the varying *given* conductivity is shown for both, using the *magnitude* $|H_m|$ of the voltage ratio H_m only and for using the *real part* $\mathrm{Re}(H_m)$ of H_m:

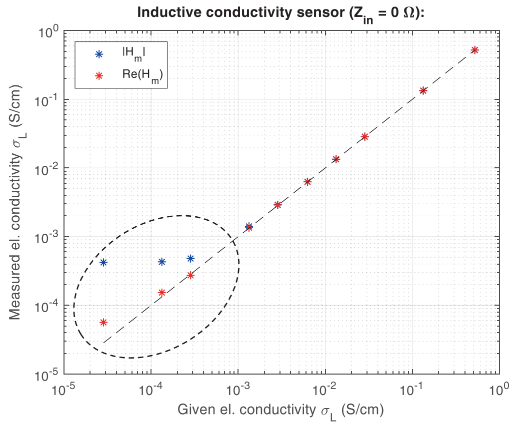

Fig. 3. Measured nominal conductivity: Magnitude and real part of voltage ratio (for $Z_{in} = 0\,\Omega$).

The results confirm that the measurement range of the sensor can be largely *extended* towards small conductivities by using the *real part* of the voltage ratio H_m and a *small* input-impedance ($Z_{in} \to 0$) in order to eliminate the influence of the unknown parasitic elements. In Fig. 4, same plots as in Fig. 3 are shown, but now for a *large* input-impedance $Z_{in} = 330\,\Omega$):

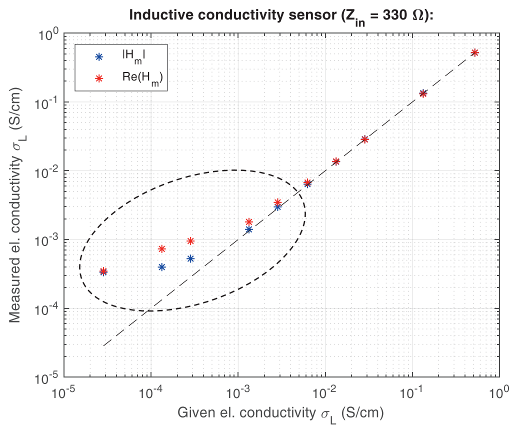

Fig. 4. Same as in Fig. 3 (but for $Z_{in} = 330\,\Omega$).

It can be seen that the measurement error is now, as expected, much larger with both, using the real part and the magnitude of H_m. In conclusion, a *trans-impedance amplifier* with a *small input-impedance* has to be used, and the *real part* of the voltage ratio has to be evaluated to guarantee for precise measurements over a large measurement range.

References

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