# Design and Potential Analysis of an Eddy Current Sensor for Inductive Conductivity Measurement in Fluids

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**Abstract:** In the scope of this paper, a first exemplary eddy current sensor for sea water conductivity measurement is developed, based on the derived sensor theory of a previous work. By a high frequency excitation, eddy currents are induced in the fluid and counter-fields measured with a sensing coil. The coils resonance point is used for amplification. The developed prototype is analysed based on a derived transfer function and FEM-Simulations. The theory is validated using an implementation. With conducted experiments on a sensor test bench, the characteristic could be confirmed and disturbances identified. It is shown that frequencies exist, where temperature influence is minimal. This work gives a perspective for a novel sensor to allow sea water conductivity measurement.

**Keywords:** Salinity; Conductivity; Inductive; Eddy Current; Sensor; Low-Cost; Uncertainty

## 1. Introduction

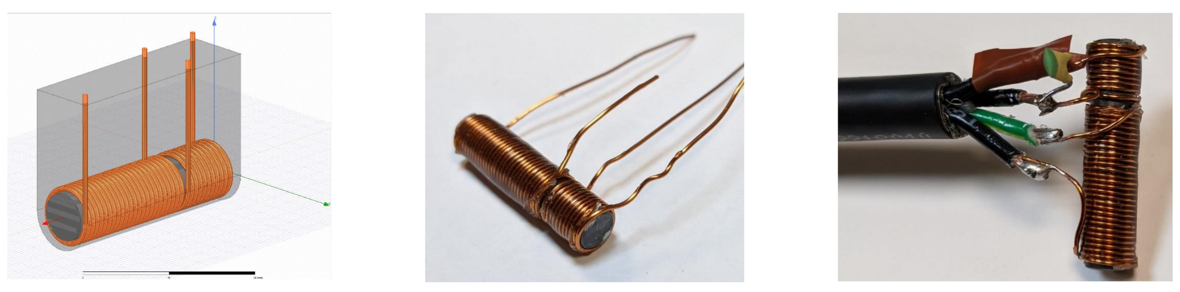
Eddy Current (EC) Sensor may have the potential to become a cost-effective alternative to Transformer Type Inductive Conductivity Sensors (TICS). An EC-Sensor generates an alternating magnetic flux in conductive fluid an measures the effects of the resulting eddy currents. In a previous work, the theory of this sensor and the derivation of a model description was performed. In the following, an implementation of the sensor is compared to the ideal model representation and FEM-Simulation results to investigate on temperature influence and possible working points.

## 2. Materials and Methods

Various experiments resulted in a sensor desing that carries two coils on a ferrite core. The coupling between both coils is determined by the magnetic field of the excitation coil minus the counter acting magnetic field of the eddy currents:

$$B = \frac{i \cdot w}{A \cdot R_{mag}} - \mu_0 \cdot \left( \sigma \cdot \frac{\delta B}{\delta t} + \varepsilon_0 \cdot \frac{\delta^2 B}{\delta t^2} \right)$$

To be able to measure this effect, the coupling has to be kept low while using a high frequency to increase $\frac{\delta B}{\delta t}$. The upper limit for the frequency is given by the resonance point of the coil which was shifted in this experiment by an additional capacitor to keep the measurement frequency below 1MHz. The same design was implemented in a FEM-Simulation and a prototype was manufactured and waterproofed by a molded housing.



(a) (b) (c)

Figure 1 (a) FEM-simulation model of sensor design (b); Sensor coils on ferrite rod; (c) Wired sensor with additional capacitor, without housing.

## 3. Experiment Setup

An experiment was conducted with the implemented prototype, where the fluids temperature and conductivity was changed over time. In a hysteresis-like progression, the conductivity was reduced from approx. 50mS/cm to approx. 15mS/cm and then increased again (fig 2). At the same time, the temperature was increased during the conductivity decrease and remained approx. constant during the conductivity increase. Figure 2 shows the peak amplitude of the sensor output next to the temperature and conductivity change. A total of 41 points were approached, for each point several measurements were conducted and the mean was derived to reduce random errors. Each measurement consists of a complete frequency response recording between 750kHz and 1Mhz.

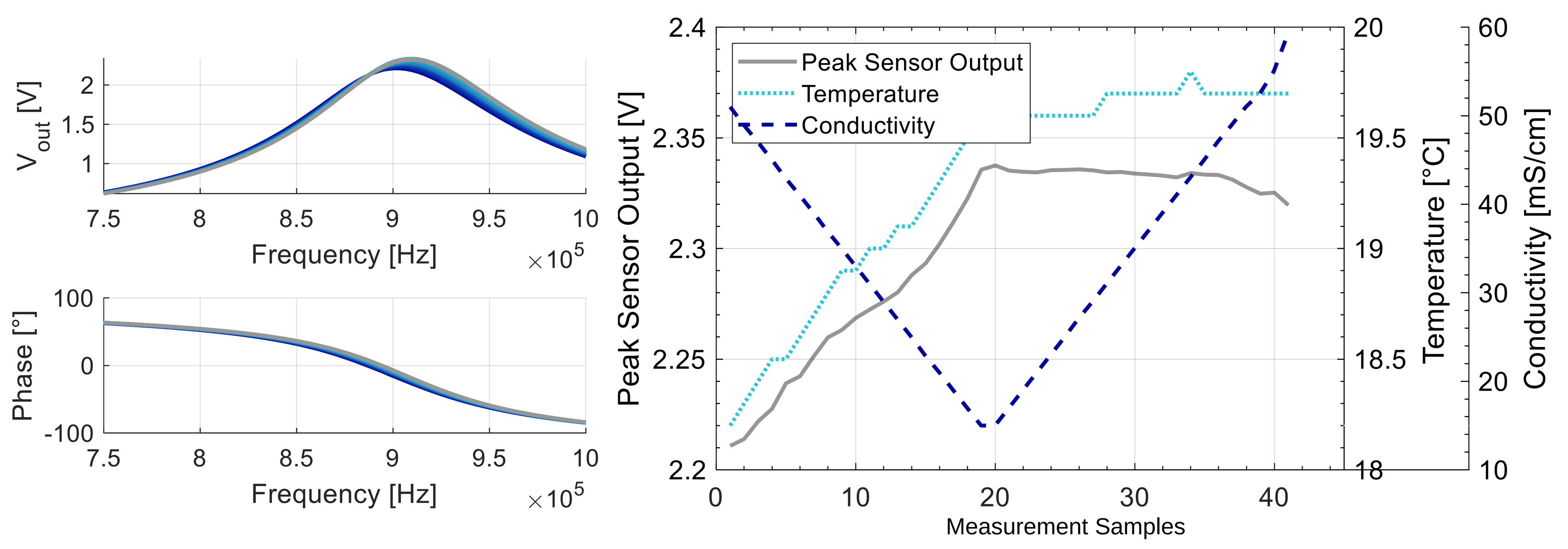



Figure 2 (left) Plot of the frequency responses of all measurement points; (right) Plot of the conductivity, temperature and peak sensor output over measurement samples

## 4. Results and Discussion

The results of the experiment show a strong and dominating temperature dependency of the sensors voltage output. This is related to the changing copper resistance and the amplification close to the resonance point. Nevertheless, both FEM simulation and TF-model indicate a correlation between sensor output voltage and fluid conductivity (fig. 3).

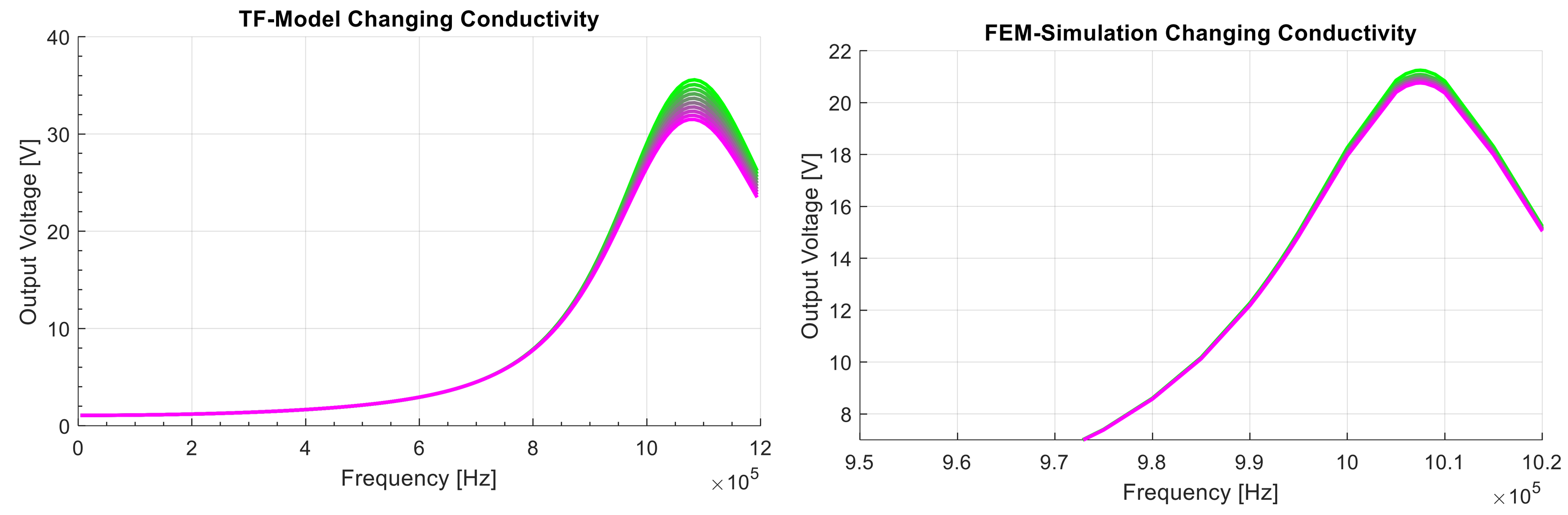



Figure 3 (left) Frequency response for equivalent transfer function model for changing conductivity; (right) Frequency response for FEM-Model for changing conductivity

The correlation to conductivity can also be seen in the experiment, when the temperature remains almost constant but the sensor voltage decreases with rising water conductivity. The equivalent model representation, derived in a previous work, indicates both temperature and conductivity behavior:

$$Z_{ges} = \frac{R_{cu} + (L + R_{cu} \cdot \mu_0 \cdot \sigma) \cdot s + R_{cu} \cdot \varepsilon_0 \cdot \mu_0 \cdot s^2}{1 + (C_p \cdot R_{cu} + \mu_0 \cdot \sigma) \cdot s + (\varepsilon_0 \cdot \mu_0 + C_p \cdot L + C_p \cdot R_{cu} \cdot \mu_0 \cdot \sigma) \cdot s^2 + C_p \cdot R_{cu} \cdot \varepsilon_0 \cdot \mu_0 \cdot s^3}$$

From the frequency response of this TF (Fig 4a) it can further be seen, that a point exists where the output voltage is independent of the temperature. In the conducted experiment, this point was found to be at 890kHz. Figure 4b shows the sensor output over water conductivity for 890kHz. The color of the measurement points represent the water temperature. It can be seen, that the output voltage is linear correlating with the conductivity but temperature has no obvious influence.

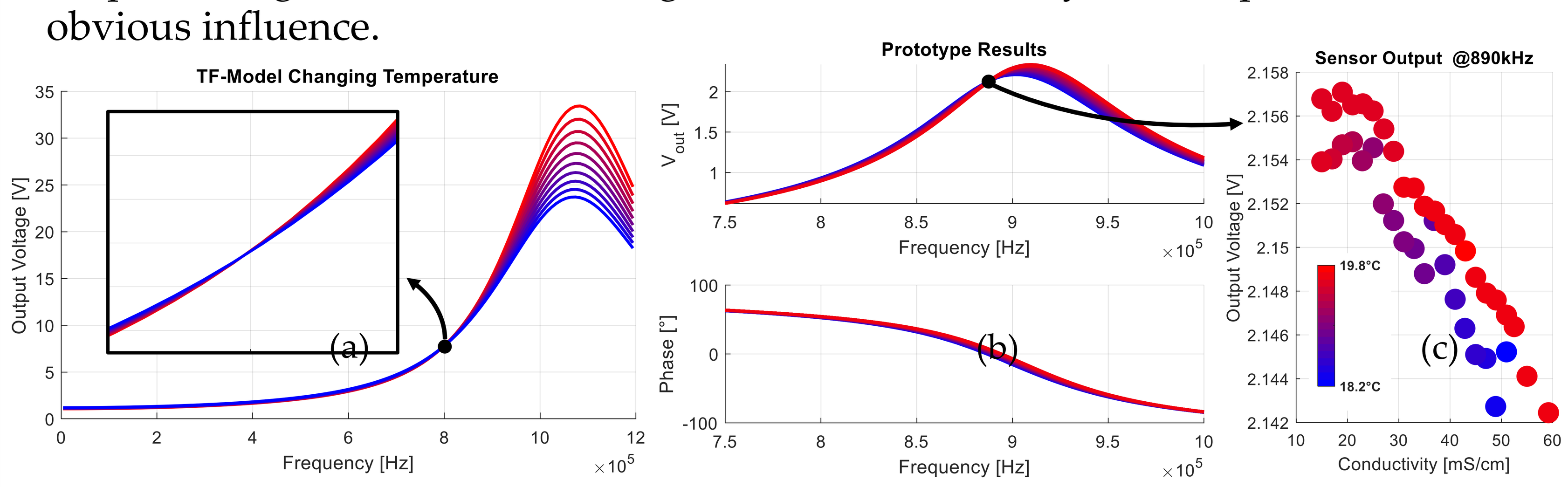



Figure 4 (a) Frequency response of equivalent transfer function model for different temperatures with indication of temperature unaffected point; (b) Experiment results with temperature related colorization; (c) Output voltage at 890kHz over water conductivity

## 5. Conclusion

The conducted experiment confirms the predicted model behaviour and indicats similar results to the FEM-simulation. It was shown, that a very simple and cost effective implementation of an eddy current sensor, allows conductivity measurement to a certain extent. Strong temperature dependencies dominate the measurement result, but it was demonstrated in the experiment as well as in the model that an operating point with very low temperature dependency exists. In this implementation, the sensor uncertainty is still to high for ocean salinity measurement but from manufacturing perspective, the eddy current sensor presents a cost effective alternative to the TICS. However, the high measurement frequency required for the EC-Sensor contributes to greater expense in secondary electronics, which can negatively impact the cost factor. In Summary, further development on eddy current sensors is necessary to develop a commercially viable instrument for salinity measurement. This paper showed the potential of the sensor and gives starting point for future research on eddy current sensors.

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