Proceedings

Uncertainty Analysis for Low-Cost Transformer Type Inductive Conductivity Sensors †

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Abstract: Transformer-type inductive conductivity sensors (TICS) are the industry standard for long-term conductivity measurement in fluids. This paper analyzes the potential of TICS as a low-cost alternative to the more cost-efficient type of conductivity cells by an implementation with reduced complexity. Sensor characteristics and performance in comparison to high precision sensor are described in the study. Linearity and hysteresis error in measurement, reproducibility and permeability influence by the temperature change are quantified through the experiments. The results were interpreted in regards to core material, geometric properties and noise shielding. Study presented in this paper provides a better understanding of performance and uncertainty characteristics in order to improve the design of low-cost transformer type inductive conductivity sensors.

Keywords: salinity; conductivity; inductive; transformer; sensor; low-cost; uncertainty

1. Introduction

Transformer-type inductive conductivity sensors (TICS) are widely used in conductivity measurements for oceanography, industry and agriculture applications and define the industry standard for hazardous environments. In comparison to conductive sensors, they have the major advantage of being protected from corrosion and biofouling. However, due to the greater complexity of the sensor design, TICS are more expensive than conductivity cell sensors. With an increasing demand for large-scale monitoring in oceanography and industry, there is a great need for low-cost inductive conductivity sensors [1]. This paper aims to explore the potential of low-cost TICS alternatives with reduced complexity, and to provide better understanding on the uncertainty characteristics.

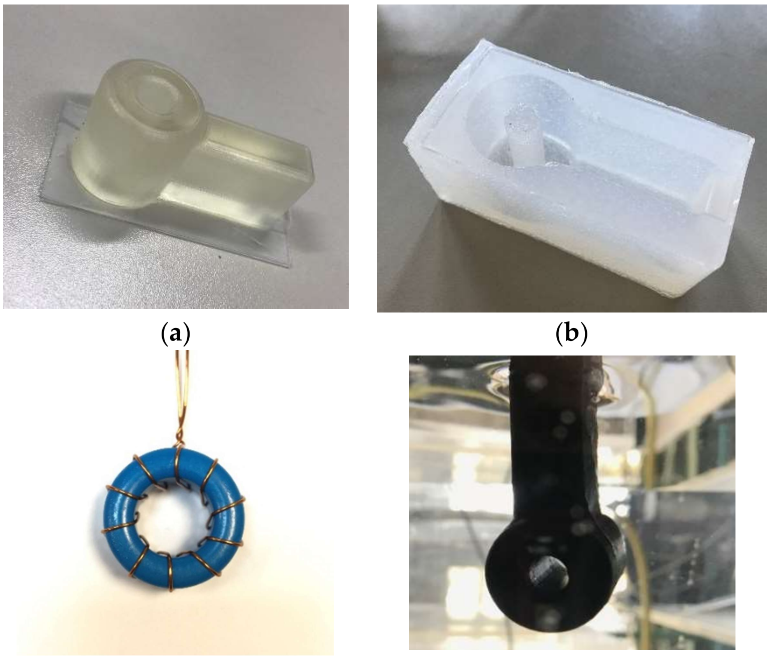
While the theory and design of TICS is well documented by numerous publications [2–6], there is little information published about the sensor uncertainty factors, as well as the implementation of low-cost TICS alternatives. In the scope of this work, a simple and cost-effective prototype was manufactured based on the results by Hui et. al [4] which provide good linearity, sensitivity and measurement range by virtual short configuration. Production materials and techniques are detailed in the methodology. Developed TICS is characterized and the measurement performance was evaluated by the accuracy of the short- and long-term reproducibility experiment which reveals the measurement uncertainty range of TICS. Hysteresis error and permeability influence was analyzed through the temperature dependency experiment. Also, the linearity error was quantified by comparing the conductivity measurement of developed TICS to a high precision industry standard inductive sensor. When assessing the experiment results, geometric imperfections from the production and selected material properties are taken into consideration. Considering the inspected uncertainties, which are related to sensor characteristics, material properties and operational conditions, outcome of this study may lead to improvement of costs-effective and high-performance transformer type inductive conductivity sensor design.

2. Materials and Methods

Transformer-type inductive sensor consists of two toroidal coils. Ferrite cores of toroidal coils are coupled through the conductive liquid surrounding them, hence the coils are qualified as driving and sensing transformer respectively [2]. Relation between the inductive voltage of sensing transformer and the alternating current of driving transformer dependents on the induced electrical current of the coupling liquid, which yields to conductivity measurement [2,3].

2.1. Manufacturing Low-Cost TICS

When designing the sensor, two identical Mn-Zn ferrite cores are selected, which have similar permeability values selected in the study of Hui et. al. [4]. Each core has 10 windings (Figure 1c), and are soldered to coaxial cable. Before making the water-resistant housing, 3D model of end product sensor is printed (Figure 1a). It is used to create casting mold by silicon rubber compound (Figure 1b). Finally, coils are placed in the silicon mold and casted by polyurethane based resin that provides sufficient protection to the coils. However, due to fast changing consistency of polyurethane blend, it is inconvenient in terms of keeping the precise geometry between coils that may have drastic impact on sensor performance. Overall cost of designed TICS is approximately $5, which is significantly lower than any alternatives.



(**a**) (**b**) (**c**) (**d**)

Figure 1. 3D printed sensor housing (**a**); Silicon based casting mold (**b**); One magnetic core with copper coil of two per sensor (**c**); End product sensor is under the conductive solution (**d**).

Table 1. Properties of selected sensor elements in TICS design.

Parameter	Value
Drive & Sense Coil Turn	10
Copper Wire Dimension	0.6 mm
Ferrite Core Material	Mn-Zn
Ferrite Core Permeability	10,000
Ferrite Core Dimension	26.6 mm × 13.5 mm × 11 mm

2.2. Experimental Setup

Aim of the experiments is the evaluation of TICS performance characteristics as cost-effective alternative on sea water conditions. Therefore, boundaries of the established test bench are limited within the oceanographic conditions of 31 °C and 55 mS/cm which corresponds to 30,000 ppm salinity. Experimental setup consists of water tank, heat exchanger, water pump, temperature sensor and high precision inductive sensor which are observed and controlled by Matlab via PLC board. Conductivity of the solution is arranged by the salinity rate. Oscilloscope and amplifier are used to generate and track TICS signals that are exported to computer for analyses. Low-pass filter applied via Matlab to TICS signals for noise reduction.

2.3. Implementation of TICS

Sensor is tested to find out the operational range of drive frequency. As it is represented in the Figure 2, amplitude of output signal linearly increases up to 150 kHz, after that sensor gain decreases and reaches the peak value at 350 kHz. For the following experiments, drive coil frequency and voltage is fixed at 30 kHz and 600 mV respectively, which restrain the magnetic loss and close to the selected drive parameters by the study of Hui et. al. [4].

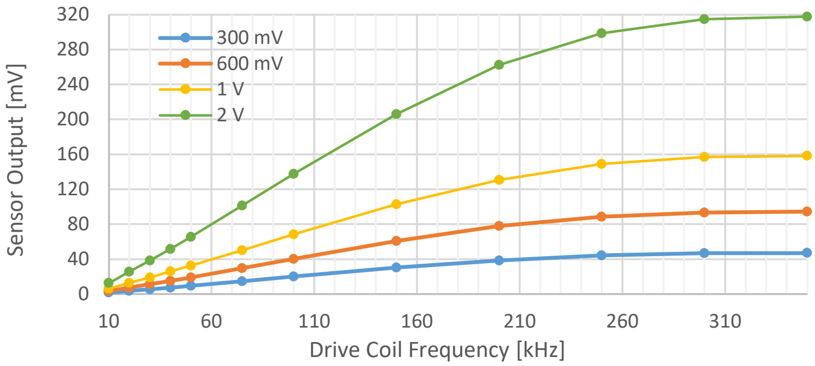
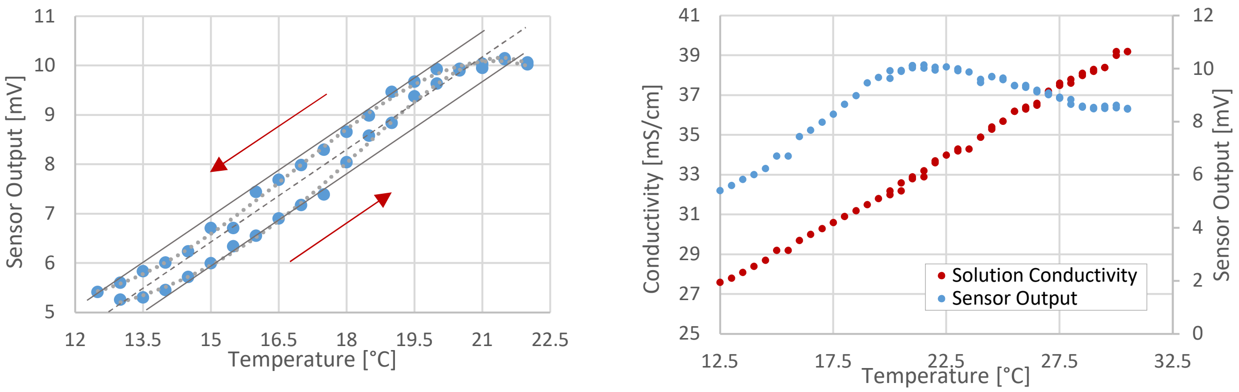


Figure 2. Sensor output displayed with respect to increasing operating frequency for drive voltages.

3. Experiment Results

3.1. Temperature Response and Hysteresis

Permeability of magnetic core is influenced by temperature and pressure change but in this study pressure change is neglected. In order to observe the temperature impact on sensor measurement, salty water content prepared at 31 °C. By keeping the salt content constant, solution cooled down to 12.5 °C (Figure 3b) and then heated back to 22 °C (Figure 3a). Figure 3, plot b indicates that the permeability reached its maximum value at 21.5 °C, while high precision sensor conductivity changed linearly.



(a) (b).

Figure 3. Dependency of ferro magnet to temperature resulted in hysteresis phenomenon **(a)**; low-cost TICS output can be approximated by two linear line, while high precision sensor conductivity increase is constant **(b)**.

Experiment shows that TICS output that is lower and higher than 21.5 °C changes approximately in two linear line. At the same time, continuous heating and cooling of conductive solution resulted in hysteresis error, which is calculated as vertical distance to linear margin lines, about ±3.42% in 16 mV scale. Impact of temperature changes were formulated, and considered in the following experiments.

3.2. Measurement Linearity

In order to observe the linear conductivity measurement behaviour of TICS sensor, water tank filled with fresh water initially. Temperature of the solution fixed at 20.5 °C during the experiment, however, small heat fluctuations were tracked and recorded. Conductivity of the solution increased up to 54 mS/cm by the gradual increase of salinity. Conductivity values were recorded by high precision sensor. TICS output amplitude change is represented in Figure 4. It is seen that sensor output instability is higher in low and high conductivity range. When the sensor measurement from 10 mS/cm is considered, mean error resulted as 0.122 mV that corresponds to 0.76% variation in the range of 16 mV.

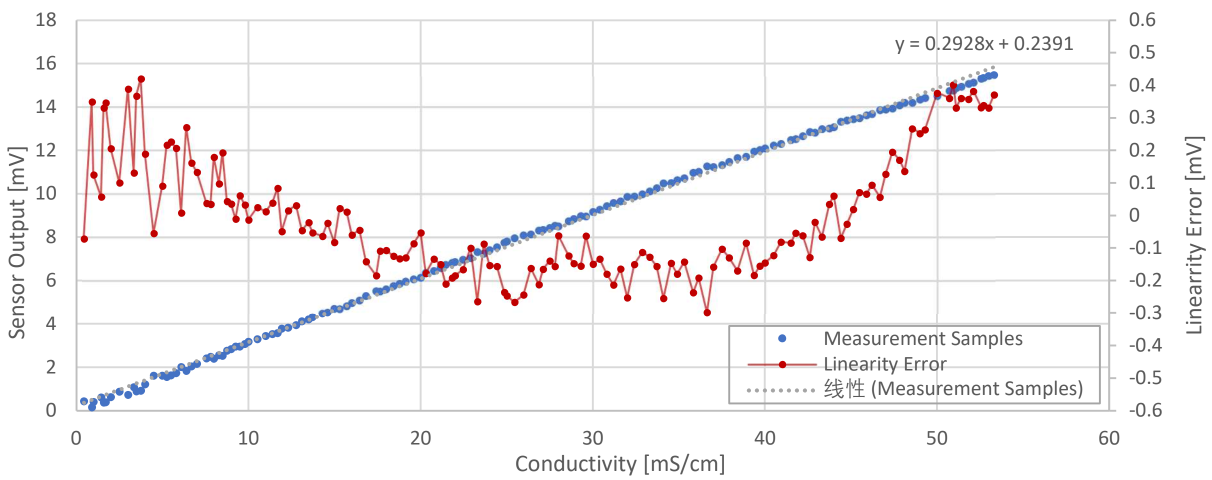


Figure 4. Cost-effective TICS output amplitude vs. solution conductivity. Linear equation of the trend line is shown on the plot. Linearity error defined as the difference from linear trend line in mV.

3.3. Measurement Repeatability

Stability of low-cost TICS might be disturbed by the surrounding electromagnetic noises and permeability influences. For that purpose, test bench is prepared such that the temperature and conductivity of solution kept constant. Continous measurements were taken as short-term, and in every 15 minutes 10 samples were taken as long-term test (Figure 5). Uncertainty range, which is defined as the largest difference between measurement points, is calculated as 0.146 mV for long-term and 0.141 mV for short-term measurements. When ocean conductivity range is considered, uncertainty of TICS correspons to 0.91% and 0.88% respectively.

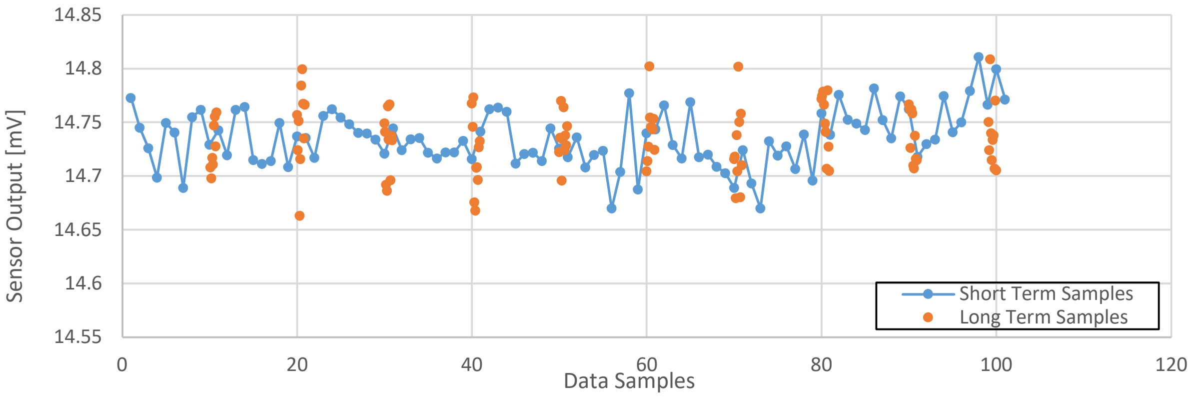


Figure 5. Uncertainty of sensor measurement is determined by the repeatability experiment.

4. Discussion

Experiment results show that developed low-cost TICS is able to provide sufficient linear behavior in conductivity measurement compared to high precision inductive sensor in ocean surface conductivity range. Linearity error indicates TICS is more prone to perturbations in lower and higher conductivity values. On the other hand, it is seen that temperature has critical impact on the permeability, and thus on the sensor signal which may result into hysteresis error around ±3.5%. However, the influence of temperature can be formulated such that the measurement drifts are compensated. Uncertainty range of TICS revealed as 0.9% approximately. Although, it is slightly higher than the design by Hui et. al. [4], which is 0.78% in the same operating range, proposed TICS possesses simpler design and lower-cost.

Due to the simplified design, manufacturing methods, selected ferromagnetic permeability and the number of coil windings, there exist imperfections in the geometry and the sensor output which leads to loss of sensor gain. Selected drive frequency of 30 kHz and amplitude of 600 mV resulted in low sensor output. Operating frequency could be increased to have higher signal amplification. Nevertheless, low-cost TICS alternative ensures sufficient performance as the basis of TICS and informs about the uncertainty considerations for further designs.

5. Conclusion

Cost-effective transformer type inductive conductivity sensor was manufactured and tested for various cases in the scope of this study. Measurement repeatability test showed that TICS uncertainty range resulted in 0.9%. Experiment outcomes gives a better understanding on the low-cost TICS production process, performance and uncertainty characteristics. Based on the presented sensor design, further improvements can be done on the manufacturing methods and material selection which will enhance the sensor gain, while providing better noise shielding. Energy consumption and the impact of pressure change could be investigated in the future studies.

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