engineering proceedings

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Proceeding Paper

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

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† Presented at the 8th International Symposium on Sensor Science, 17–28 May 2021; Available online: https://i3s2021dresden.sciforum.net/.

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 cost-effective 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 influenced by the temperature change are quantified through the experiments. The results were interpreted in regard to core material, geometric properties and noise shielding. The 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

Citation: Kandur, Y.; Harms, J.; Kern, T.A. Uncertainty Analysis for Low-Cost Transformer-Type Inductive Conductivity Sensors. *Eng. Proc.* **2021**, *6*, 52. https://doi.org/10.3390/I3S2021Dresden-10145

Academic Editors: Gianaurelio Cuniberti and Larysa Baraban

Published: 17 May 2021

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.

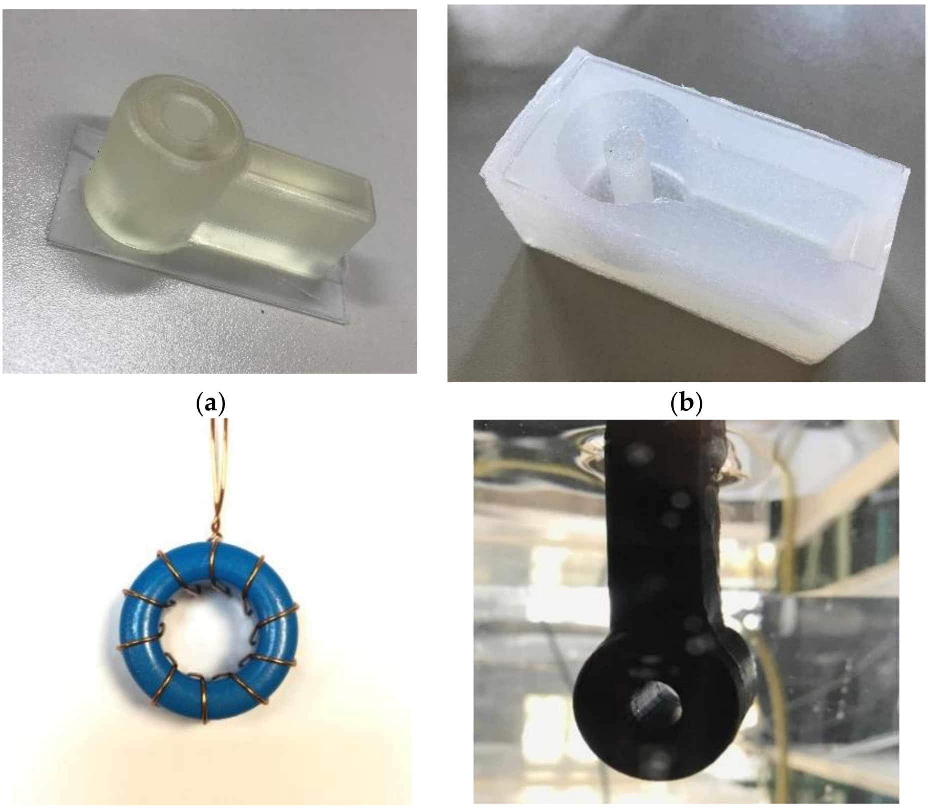
While the theory and design of TICS is well documented by numerous publications [2–6], there is little information published about the sensor uncertainty factors, as well as the implementation of low-cost TICS alternatives. In the scope of this work, a simple and cost-effective prototype was manufactured based on the results of 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 were 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 were analyzed through the temperature dependency experiment. Additionally, 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, the outcome of this study may lead to improvement of costs-effective and high-performance transformer-type inductive conductivity sensor design.

2. Materials and Methods

The 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 the sensing transformer and the alternating current of the driving transformer depends 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 were selected, which have similar permeability values selected in the study of Hui et al. [4]. Each core has 10 windings (Figure 1c), and is soldered to coaxial cable. The properties of the selected coils can be seen in Table 1. Before making the water-resistant housing, a 3D model of end product sensor was printed (Figure 1a). It was used to create a casting mold with silicon rubber compound (Figure 1b). Finally, coils were placed in the silicon mold and casted by polyurethane-based resin that provides sufficient protection to the coils. However, due the 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. The 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

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

2.3. Implementation of TICS

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

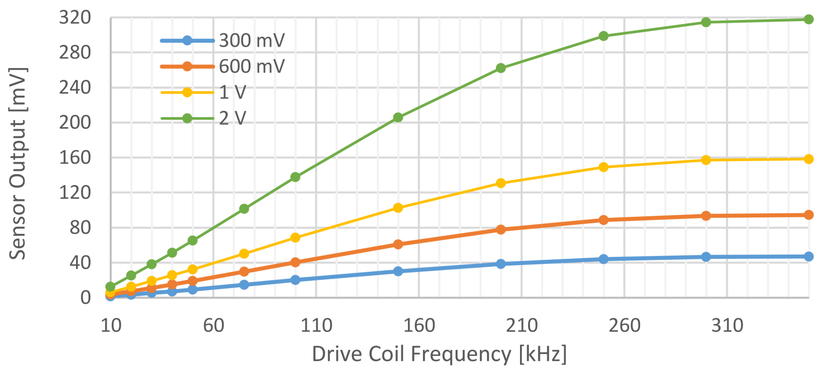


Figure 2. Sensor output displayed with respect to increasing operating frequency for drive voltages.

3. Experiment Results

3.1. Temperature Response and Hysteresis

Permeability of the 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 was prepared at 31 °C. Whilst keeping the salt content constant, the solution was cooled down to 12.5 °C (Figure 3b), and then heated back up 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.

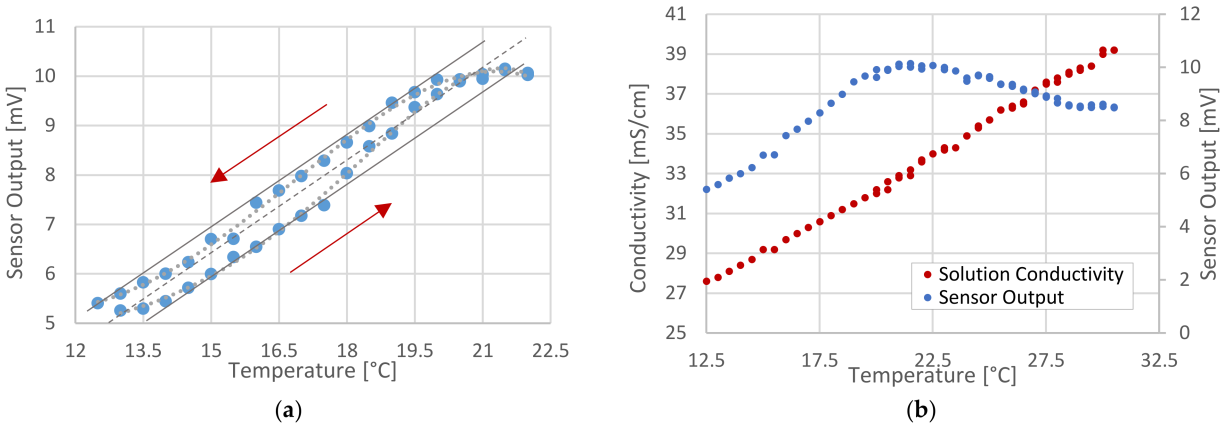


Figure 3. Dependency of ferro magnet on temperature resulted in hysteresis phenomenon (**a**); low-cost TICS output can be approximated by two linear line, while high precision sensor conductivity increase is constant (**b**).

The experiment shows that TICS output that is lower and higher than 21.5 °C changes approximately in two linear lines. At the same time, continuous heating and cooling of the 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 the TICS, the water tank was filled with fresh water initially. Temperature of the solution was 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 in salinity. Conductivity values were recorded by a high precision sensor. TICS' output amplitude change is represented in Figure 4. It can be seen that sensor output instability is higher in the low and high conductivity range. When the sensor measurement from 10 mS/cm is considered, mean error was 0.122 mV, which corresponds to 0.76% variation in the range of 16 mV.

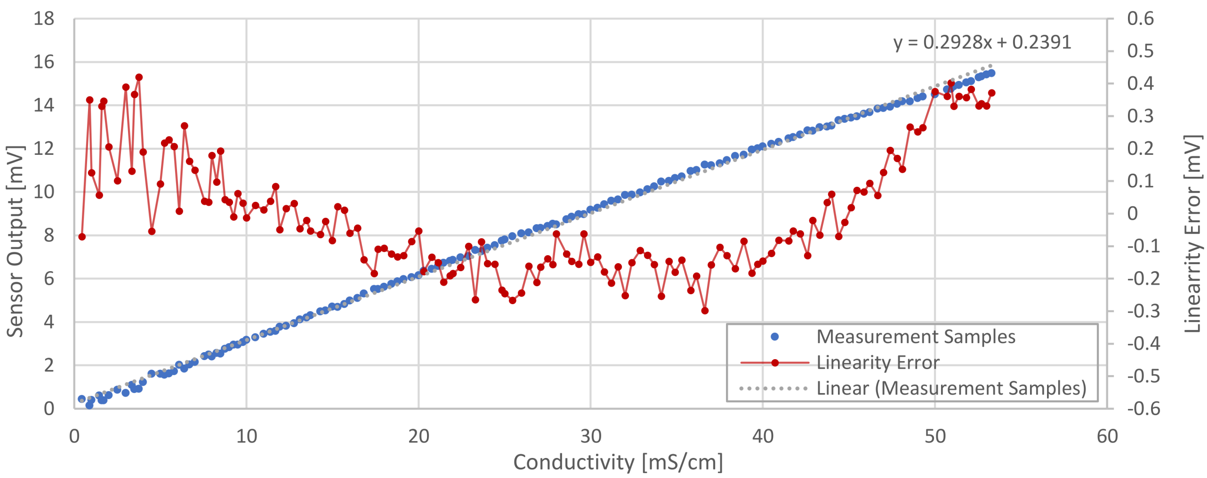


Figure 4. Cost-effective TICS' output amplitude vs. solution conductivity. Linear equation of the trend line is shown on the plot. Linearity error defined as the difference from linear trend line in mV.

3.3. Measurement Repeatability

Stability of the low-cost TICS might be disturbed by the surrounding electromagnetic noises and permeability influences. For that purpose, a test bench is prepared such that the temperature and conductivity of the solution are kept constant. Continous measurements were taken as a short-term test, and every 15 min 10 samples were taken as a 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 corresponds to 0.91% and 0.88%, respectively.

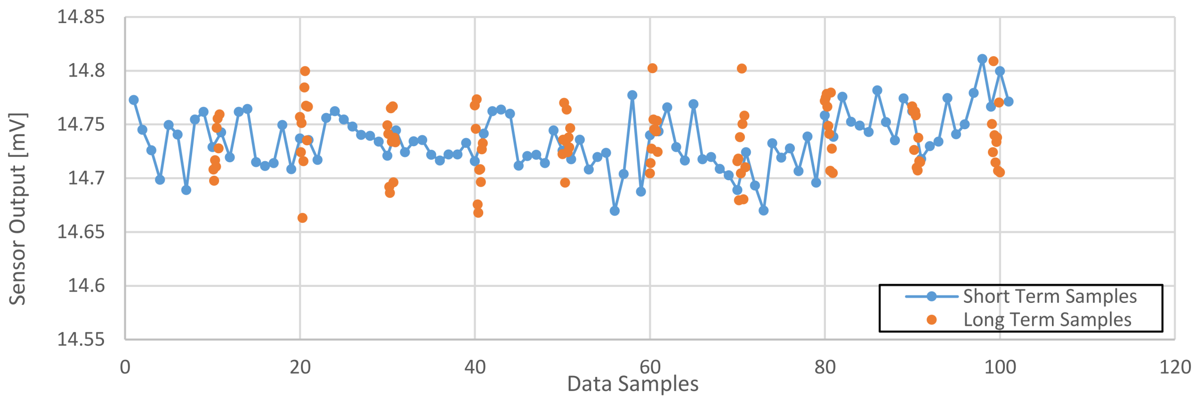


Figure 5. Uncertainty of sensor measurement is determined by the repeatability experiment.

4. Discussion

Experiment results show that the developed low-cost TICS are able to provide sufficient linear behavior in conductivity measurement compared to a high precision inductive sensor in ocean surface conductivity range. Linearity error indicates that TICS are 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 in hysteresis error of around ±3.5%. However, the influence of temperature can be formulated such that the measurement drifts are compensated. Uncertainty range of TICS was revealed to be approximately 0.9%. Although this is slightly higher than that of the sensor designed by Hui et al. [4], which is 0.78% in the same operating range, the proposed TICS possess 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, the low-cost TICS alternative ensures sufficient performance as the basis of TICS and provides information about the uncertainty considerations for further designs.

5. Conclusions

A cost-effective transformer-type inductive conductivity sensor was manufactured and tested for various cases in the scope of this study. The measurement repeatability test showed that TICS' uncertainty range was 0.9%. Experiment outcomes provide a better understanding on the low-cost TICS' production process, performance and uncertainty characteristics. Based on the presented sensor design, further improvements can be made to 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 future studies.

Author Contributions: Conceptualization, J.H. and T.A.K.; methodology, Y.K. and J.H.; software, Y.K.; validation, Y.K. and J.H.; formal analysis, Y.K. and J.H.; investigation, Y.K.; resources, T.A.K.; data curation, Y.K.; writing—original draft preparation, Y.K.; writing—review and editing, J.H. and T.A.K.; visualization, Y.K.; supervision, T.A.K.; project administration, J.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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