Electrical Impedance Tomography Spectroscopy for Ice and Water Mixtures

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Abstract.
The power that is necessary for heating wings and other aircraft surfaces in order to avoid ice formation is high. In this paper, the idea of a system is presented that could be used in the future for increasing safety and efficiency during flight by determining how the ice is being formed. Electrical Impedance Tomography Spectroscopy (EITS) is used to map water and ice mixtures formed on electrodes using Finite Element Method (FEM) simulations.

1. Introduction
Ice formation on an aircraft surface can be dangerous and in order to avoid it many de-icing and anti-icing methods exist. However, heating systems currently used have a very high power consumption [1]. By determining ice formation with an intelligent and portable system, the efficiency and safety could be increased.

Wireless sensor networks can be used on many systems and they can bring advantages such as weight reduction, ease of maintenance and also better monitoring capability [2]. In [3], a wireless sensor system was developed for ice detection on aircraft surfaces using a thin, flexible and portable sensor. In this system, ice could be detected, but it was outside of the scope to reconstruct the ice formation or determine which type of ice was being formed, which is something we aim at in this paper.

Some efforts were also made in [4], [5] and [6] using a wireless portable system for pressure distribution measurement on aircraft and a similar structure could also be used for ice measurement.

Electric Impedance Tomography (EIT) allows the determination of spatial distribution of materials based on their permittivity values. However, static permittivity is often not enough to distinguish materials. In Electrical Impedance Spectroscopy (EIS), the frequency dependent characteristics of materials can be analyzed, including changes in permittivity which can occur due to relaxation effects. The purpose of this article is to combine both methods in order to better reconstruct and distinguish ice and water mixtures using EITS.

2. Background
2.1. Complex Permittivity
The susceptibility is related to the permittivity by the relation \( \varepsilon = 1 + \chi \) and is defined by
\[ \chi = \chi' + i\chi'' \]  
\[ \chi' = \frac{\chi_s}{1 + \omega^2 \tau_D^2} \]  
\[ \chi'' = \frac{\omega \tau_D \chi_s}{1 + \omega^2 \tau_D^2} \]

where \( \chi_s \) is the static susceptibility, \( \omega \) the angular frequency and \( \tau_D \) is the relaxation time [7].

2.2. Ice and Water Mixtures
The determination of the permittivity in case of a mixture of different materials can be difficult and many models exist in the literature to describe such mixtures.

In case we have ice as host medium with water inclusions of volume fraction \( f \), the resultant permittivity is given by Equation 4 according to a model proposed in [8], where \( \varepsilon_w \) is the permittivity of water and \( \varepsilon_i \) is the permittivity of ice.

\[ \varepsilon = \varepsilon_i + \frac{1+2f}{3} (\varepsilon_w - \varepsilon_i) \]

2.3. Electrical Impedance Tomography Spectroscopy
EIT allows an image to be reconstructed according to the different permittivities of materials [9]. EIT is traditionally performed with electrodes surrounding the Region of Interest (ROI). However, for this project a planar and flexible structure will be considered, which allows the sensor to be easily placed on any surface. Many reconstruction algorithms already exist for EIT, and since low computational effort is a priority for this application, the focus of this paper is on non-iterative algorithms, such as fast Bayesian methods (BMMSE), like Optimal First Order Approximation (OFOA) and Optimal Second Order Approximation (OSOA) [10].

While in EIT the permittivities of materials are used to reconstruct the material distribution over time in a ROI, in EIS the behavior of a material in the frequency domain is investigated, such as shown in [11] and [12] for water and ice. When combining these two techniques in EITS it is possible to get a better distinction between materials.

Studies on EITS have been made on the last years, but mainly for the classical circular region of interest. The importance of data fusion and potential data fusion methods for EITS are described in [13]. A multifrequency system for EIT was developed and validated with experiments in [14] for human head imaging using frequency difference and time difference images. In [15], a study was made on the feasibility of integration of EIS and EIT to perform EITS using a frequency-time difference imaging method and different measurements setups with promising results.

3. Methodology
3.1. Simulation
Matlab was used for the FEM simulations, where a structure was created consisting of 8 electrodes on the lower surface of the ROI and a material that varied its composition was located on the electrodes. For each frequency, one set of measurements was obtained and this information was fused in order to create one image to identify the fraction of materials.
Each measurement matrix was formed by the measurements between each of the electrodes at each frequency, considering that one of the electrodes at a time acts as a transmitter while the others are receivers. The values measured are the capacitance values between these electrodes.

In this paper, the complex impedance measurements were made for different frequencies, from 100 Hz until 1 MHz, while the material presented complex permittivity characteristics which are frequency dependent. In order to improve simulation efficiency, the designed mesh has a structured form that increases its size according to the distance from the electrodes in order to have a better resolution for thinner layers.

3.2. Reconstruction

In this paper, we use OFOA and OSOA methods [16], which follow the Bayesian Linear Minimum Mean Square Error (LMMSE) approach with

$$\tilde{\varepsilon}_{LMMSE} = Wy + B$$

$$W = C_{\varepsilon y}C_{yy}^{-1}$$

$$B = \bar{\varepsilon} - W\bar{y}$$

where $C_{yy}$ is the autocovariance matrix of the measurements, $C_{\varepsilon y}$ is the cross-covariance matrix between the measurements and the permittivities, $\tilde{\varepsilon}$ is the expected value of the permittivity and $\bar{y}$ the expected value of the measurements. In the OSOA method, the measurement vector $y = (y_1,...,y_n)^T$ is replaced by $\tilde{y} = (y_1,...,y_n,y_1^2,...,y_n^2)^T$.

For our application, instead of using the measurement matrix for one frequency, all frequencies were considered for each prior. Therefore, the coefficients are obtained for measurement at all specified frequencies. The prior distribution was created as a combination of water and ice following Equation 4 varying from pure ice to pure water. Two different compositions were placed on the ROI to obtain the priors, which were represented by two circles with radius and center defined randomly. The reconstruction results in two images, which represent the water and ice fraction of the material under analysis, which can vary between 0 and 1.

4. Results

In Figure 1 an example is shown where the OFOA and OSOA methods were used to reconstruct water fractions on a substance formed by two different layers. In the same way, in Figure 2 the ice fraction is shown, which is complementary.

![Figure 1: Expected and reconstructed (OFOA and OSOA) water fraction, respectively.](image-url)
5. Conclusion

The determination of how ice is formed on the surface of an aircraft could bring many benefits for the aviation industry, increasing safety and also the efficiency of de-icing and anti-icing systems during flight.

In this paper, the idea of a measurement system was described that could reconstruct the fractions of ice and water present in a material. It could be shown using FEM simulation results that the reconstruction of different ice and water formations can be done using EITS.

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