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Monitoring of icing behavior based on signals from a capacitance sensor

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ABSTRACT

In the work, we proposed a new method to monitor the icing behavior. To this end, a sensor system based on the multi-electrode capacitance is used to measure the ice thickness in both lab and field investigations. It is demonstrated that such a system shows very promising applications for measurements of the ice thickness of river and sea. The experimental results can provide reliable data for studies of the ice growth. In the practice, the designed and manufactured apparatus can present the ice cap of sea. The subsequent quantitative analyses on the data indicate the reliability and accuracy of the apparatus for monitoring sea ice.

1. Introduction

Sea ice thickness directly affects the thermodynamic interaction of the atmosphere and marine environments. It has long been considered a key indicator reflecting climate change in polar regions [1,2]. However, little is known about ice thickness changes. Sea ice plays an important role in the global radiation balance and global climate due to its smooth surface and the accumulated snow thereon. Moreover, continuous, real-time automatic monitoring of ice thickness on fixed sites is a difficult problem in ice thickness detection technology. At present, four methods are mainly employed in sea ice thickness observation. These are, manual hole-drilling measurements, remote sensing measurements, sonar measurements, and airborne (ship) electromagnetic sensing measurements.

Manual hole-drilling was the earliest ice thickness measurement used. The method is highly accurate, very reliable, and has been widely used. However, it cannot realize fixed-site real-time measurement. Moreover, it requires high labor intensity and shows low efficiency. Thus, it is merely used to make measurements at key points. In addition, this method cannot be used during ice forming and thawing periods for the sake of safety.

Remote sensing refers to the measurement of a wide range of ice structures using measurement devices carried by satellites [3–5]. Satellite remote sensing contributes much to the monitoring of a wide range of ice and is widely utilized. However, due to the satellite's altitude, picture resolution is low. Therefore, this method can only be used to obtain characteristic ice information on a large scale. It is not capable of acquiring ice parameters on medium and smaller scales. Furthermore, it is relatively easily influenced by weather.

In sonar measurement, a high frequency transducer is used to emit different forms of signals and the time-delay between the reflected signals from the ice–air and ice–water interfaces detected. The ice thickness can then be calculated from the time difference between the echo signals from the two interfaces and the sound velocity in the ice in the measurement area [6,7]. This method shows the optimum under-ice resolution and can avoid the influence of ice properties. However, it is only able to detect the ice thickness below the waterline of the ice layer.

Airborne radar measurements began to be used in sea ice observation in the middle 1980s [8,9]. In this method, the ice thickness is obtained by analyzing electromagnetic echo signals and calculating the distance between the upper and lower surfaces of the ice. The main commercial products used include the EM-31 ice and snow detector, etc. [10]. The method can be directly applied in moving situations and can collect a large amount of data in a short period of time without damage to the ice. Thus, the influences of summer and device installation on the ice melting rate are reduced. However, in this method, the contours or 'ups and downs' of the ice surface are all included in the bottom surface morphology.

Lei et al. [11] have developed a fixed-site magnetostrictive sea ice thickness measurement device. The device was adopted to monitor the sea ice for more than half a year and is capable of monitoring sea ice thickness to a precision of ±2 mm. Unfortunately, due to

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certain factors, such as the inability of the power supply used to provide the long-term, unattended mechanical power the system requires, the equipment is still at present in a state of improvement. Therefore, a new device is designed in the current study to measure changes in the snow/ice thickness at fixed sites. It aims to monitor the sea ice thickness in time to a precision of 1 cm. Moreover, the power consumption of its power supply is low. A 12 V spirally wound lead acid battery with a capacity of 80 Ah can ensure normal working of the whole device set for one year. In addition, the whole device set has a low cost and is suitable for being laid on a large area of sea ice. From March to October, 2012, this device was applied to the ice surface and ice cap near the Station.

This study first introduces the basic principles involved, as well as the design and production process used to construct the system for ice thickness detection by coplanar multi-electrode capacitance sensors and corresponding system. Then, it discusses application of this apparatus in the detection tests carried out on the sea ice. The accuracy of the apparatus is also analyzed. Finally, the in situ application and problems encountered with it are discussed and solutions and improvement measures for these problems outlined.

2. Theoretical considerations

Brine and ice have contrasting electrical properties in-terms of both charge transport efficiency and charge transport mechanics. In brine, the differential movement of the abundant free salt ions constitutes an electrical current, while conduction in ice is facilitated by imperfections in the crystalline lattice [12]. These defects propagate through the structure by reorientation of molecules and reordering of bonds, a phenomenon known as protonic conduction. Pure ice is a poor electrical conductor because the defect concentration is low, while any brine included in the ice has a high conductivity. Electrical methods can be performed on the ice in situ and they offer the possibility of automated sea ice monitoring. The measurement of ice thickness using coplanar capacitance sensors based on the different permittivities of sea ice and water. The basic principle of this apparatus centers on the capacitance end effects of the capacitance sensor. Fig. 1(a) illustrates the basic working principle of the coplanar capacitance sensor. The apparatus is composed of exciting and receiving electrode plates. The plates are isolated by grounded shield layers. The electric field variation between the exciting and receiving electrode plates depends on the ice thickness and so the latter may be measured indirectly. In 1969, Noltingk [13] first proposed a high-precision measurement system based on the end effects of coplanar capacitance. In addition, he implemented the design structures of two sensors, namely, a giant coplanar capacitance sensor and an annular coplanar capacitance sensor. The two sensors both utilized the capacitance end effect to measure micro-distances. In 1976, Noltingk, Nye and Turner [14] presented a mathematical analysis of the coplanar capacitance sensor for polar plates that are rectangular in structure. In 1993, Luo and Chen [15] mathematically analyzed the annular coplanar capacitance sensor and established the corresponding mathematical model. In more recent years, coplanar capacitance sensors have been widely used for material thickness measurement [16] moisture or humidity measurement, etc. Sundara-Rajan et al. [17] used coplanar capacitance to determine the moisture content in paper. Zyuzin et al. [18] adopted coplanar capacitance to detect the moisture content in food, such as biscuits, etc. Chen [19] employed coplanar capacitance to perform nondestructive inspection of multi-layer structures. Nassr [20] also used coplanar capacitance to inspect the moisture content of a medium with complex structure.

Fig. 1(b) shows the electric field distribution produced in the media layers beneath the sensor. Since the electric field strength decays exponentially with the thickness of the measured medium, the permittivity of the medium closer to the fixed electrode surfaces has a larger impact on the capacitance between the coplanar electrodes [21]. In the cross-section shown in Fig. 1(b), a coplanar sensor is created by two electrodes of width s spaced $2g$ apart on two substrate layers of heights h_1 and h_2 (from the upper surface) and dielectric permittivities ε_r, respectively. In the analysis, the electrode strips are assumed to have zero thickness and infinite conductivity. Also, the strip length l is larger than the width ($l > s$) to avoid end effects. The capacitance between the two electrodes due to the substrate layers is given in closed form as

$$C = \varepsilon_0 \varepsilon_r \frac{K(k_0')}{K(k_0)}, \tag{1}$$

where $K(k)$ is the complete integral function, ε_0 is the vacuum permittivity (F m^{-1}), and k_0 and k_0' are functions of s and g. They are given by

$$k_0 = \frac{g}{s+g}, \quad \text{and} \quad k_0' = \sqrt{1-k_0^2} \tag{2}$$

It can be seen from Eq. (1) that the variation in the capacitance of the coplanar electrodes shows a certain functional relationship with the permittivity of the medium close to the electrode. Since water, ice, and air present different permittivities at a certain environmental temperature, a plurality of electrodes can be installed in parallel in the same plane to constitute a coplanar multi-electrode capacitance sensor. Such a sensor can then be installed vertically in the ice and the water under the ice. Since the media contacting the electrodes are ice, water, or air, the capacitances between each electrode and adjacent electrodes are different. Thus the vertical measurement of ice thickness can be realized.

The coplanar multi-electrode capacitance ice thickness measurement is based on the model in Fig. 1. Through the contact made with different media (such as ice and water) the exciting metal electrode is affected and the electric field around the metal electrode is changed. The capacitance of the metal electrode is thereby altered. It is assumed that C_3 is the capacitance composed by one single capacitance electrode plate (A in the diagram) and its adjacent grounding electrode plates. The air's permittivity is ε_0, ε_r is the dielectric coefficient of the medium, and A is the electrode plate area. If ε_r fluctuates, the capacitances C_1, C_2, and C_3 are changed.

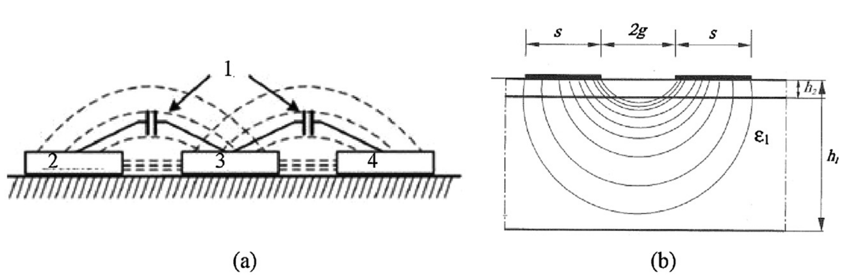

Fig. 1. Electric field model of a multi-electrode capacitance. The basic working principle of the coplanar capacitance sensor. 1 – electric field between the electrode plates. 2,4 – exciting electrode plate. 3 – receiving electrode plates; (b) illustrates the field distribution in the layers of the underlying medium.