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Freshwater ice thickness apparatus based on differences in electrical resistance and temperature

Liqin Cui [a,b], Jianmin Qin [a,b,*], Xiao Deng [a,b]

[a] College of Physics and Optoelectronic, Taiyuan University of Technology, Taiyuan, China
[b] Key Laboratory Advanced Transducers and Intelligent Control System, Ministry of Education, Taiyuan University of Technology, Taiyuan, China

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ABSTRACT

An apparatus for monitoring freshwater ice thickness using the differences in the electrical resistance and the temperature of air, ice, and water is developed. The principle and components of the apparatus are presented. Using the proposed apparatus, the electrical resistance characteristics of air, ice, and water from 12 to −55 °C were studied in the laboratory. Field measurements using this apparatus were conducted in the Wanjiazhai Reservoir in the upper Yellow River for approximately four months during the winter of 2012–2013. The results showed that the recorded ice thickness agreed with the drill-hole measurements. The differences between the recorded and the drill-hole data are between 0 and 0.02 m. The new apparatus can continuously and automatically operate in freshwater ice. It provides an effective method for monitoring the ice thickness and temperature profiles in the air, ice and underlying water.

1. Introduction

The monitoring of freshwater ice is important for the generation of hydropower, the forecast and mitigation of floods, navigation in inland waters, and the construction of winter roads (Leconte et al., 2009). The presence or absence of ice in rivers or lakes during the winter months is vital for both the regional climate and weather events. Ashton (2011) noted that the thickness is probably the most important characteristic of river and lake ice. The temperature profiles play an important role in ice thickness change. The heat exchange caused by the temperature differences among air, ice, and water is an important factor in the growth and melting of ice. At the beginning of winter, when the temperature of water drops to the freezing point, additional heat loss causes supercooling and ice formation (Shen, 2010). Subsequently, an ice cover forms, and the ice layer gradually becomes thicker as the temperature decreases. At the beginning of spring, the thickness of the ice cover decreases, and the ice melts as the temperature increases. Therefore, measurement of the temperature profiles during the growth and melting processes of ice is important. In the northern regions of China, a drill-hole measurement is the most common method for obtaining the ice thickness. The temperature observed is typically limited to the air temperature rather than the temperature profiles. Thus, the continuous and automatic monitoring of the ice thickness and temperature profiles throughout the growth and melting processes of ice is essential to provide more understanding on the thermal growth of ice cover.

Determination of the ice thickness relies on two general methods. One is the establishment of a numerical model for ice and a simulation of its thickness by solving heat conduction equations. The other is in-situ measurements, which include contact and noncontact methods. Contact methods such as drill-hole and thermal-wire measurements are recognized as the most reliable detection methods (Heil, 2006; Perovich et al., 2003). A drill-hole measurement involves manually drilling holes on an ice surface to measure the ice thickness. This measurement method is not only risky and labor intensive but it is also time-consuming and yields insufficient data. A thermal-wire measurement measures the ice thickness in a semi-automatic manner. When measuring the ice thickness using this method, the operator needs to heat a wire to melt the ice around the wire and then manually retract the wire and record the ice thickness. A magnetostrictive-delay-line positioning apparatus has been applied in the Antarctic with an accuracy of up to 0.2 cm (Lei et al., 2009), but the apparatus cannot operate for a long time because it consumes a considerable amount of energy. Owing to their shortcomings as indicated above, contact measurement methods fail to satisfy the monitoring requirement of a high temporal resolution for the ice thickness. Noncontact measurements such as satellite remote sensing (Drucker et al., 2003; Duguay and Lafleur, 2003; Leconte et al., 2009; Unterschultz et al., 2009), the infragravity wave velocity difference (Wadhams and Doble, 2009), helicopter-borne measurement (Arcone, 1991), and radar penetration (Galley et al., 2009; Gogineni et al., 2007; Holt et al., 2009) can measure the ice thickness over a large area. However, these methods suffer from the disadvantages of low accuracy and high cost. Moored upward-looking sonar is recognized as the most effective measurement method, but its accuracy has yet to be demonstrated (Brown and Duguay, 2011; Drucker et al.,

* Corresponding author at: College of Physics and Optoelectronic, Taiyuan University of Technology, Taiyuan, China. Tel.: +86 13700502213.
E-mail address: qinjianmin@tyut.edu.cn (J. Qin).

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2003; Laura and Claude, 2011). Although numerical modeling has been well developed (Duguay et al., 2003; Launiainen and Cheng, 1998), the accuracy of ice-thickness measurement has not significantly improved.

A traditional thermistor string has been used to measure the air temperature and the temperature profile of sea ice, but it is limited by its high cost and complex circuit (Perovich et al., 1997; Peterson et al., 1991).

From the above-mentioned methods, it is recognized that achieving continuous and automatic monitoring of the ice thickness and temperature profiles is difficult. If the data sampling frequency is considered, some of these traditional methods must be improved. Otherwise, some information would be lost because of the longer data sampling time intervals. On the basis of these traditional methods, we attempt to develop a method to continuously and automatically measure the freshwater ice thickness and temperature profiles. Further, it is necessary to develop an automatic apparatus with a high sampling frequency for monitoring the ice thickness and temperature profiles. We propose a measurement apparatus based on the differences in the electrical resistance and temperature among air, ice, and water. This apparatus can automatically operate after installation without repetitive manual operation. The data sampling interval can be set from 1 to 60 min. If necessary, we can obtain more data sets at different times of the day. This apparatus is suitable for measuring the ice thickness and temperature profiles and for physical studies on the growth and melting processes of ice. The developed apparatus was utilized to monitor the ice thickness and temperature profiles in the Wanjiazhai Reservoir for approximately four months during the winter of 2012–2013.

In this paper, we first discuss the detection principle and components of the proposed apparatus. Then, we introduce the ice-thickness algorithm and the DS18B20 temperature-sensor calibration method. The measurement results from the laboratory and field experiments are also described.

2. Design principle

According to the electrical properties of each medium, natural water, which contains conductive impurities, is a good electrical conductor, and air is an insulator. Ice possesses a poor conductivity, and it can be considered as a semiconductor in the temperature range from −20 to 0 °C (Qin and Shen, 2004; Qin et al., 2008). Therefore, the equivalent electrical resistance R_x of air, ice, or water is introduced to a circuit using two stainless-steel screws as two electrodes, as shown in Fig. 1. It is noted that surface coating problems on the stainless-steel electrodes, such as rust, oxidization, and electrolysis, are unavoidable. To ensure the quality of the stainless-steel screws and prevent the rusting of electrodes as much as possible, a rust test will be conducted in a water sample (tap water and river water) before the manufacture of the ice-thickness sensor. Further, the electrodes are not easily oxidized owing to a passivation treatment, and they are not easily electrolyzed in water or ice because the current passing through them is very low.

The two electrodes are detection and return electrodes, respectively. They are connected to the circuit using the decoding pins of a complex programmable logic device (CPLD) multiplexer switch and an analog multiplexer (ADG732). V_{cc} is a fixed DC power supply (3.3 V); R_0 is the divider resistance; V_0 is the voltage across R_0, which is the so-called detection voltage; and R_x is the equivalent electrical resistance of air, ice, and water between the two electrodes. According to Eq. (1), its value can be calculated by measuring V_0.

$$R_x = (V_{cc} - V_0)/(V_0/R_0) = R_0(V_{cc}/V_0 - 1) \quad (1)$$

The values of V_0 are different because of the difference in the equivalent electrical resistance of air, ice, and water R_x. To simplify the calculation, the state of the media between the two electrodes is determined according to the different values of V_0, rather than the values of R_x. In addition, the vertical three-dimensional space of freshwater ice can be divided into air, ice, and water layers, which have different electrical characteristics. Fig. 2 shows that the measured three-dimensional vertical space is divided into n level detection layers spaced at intervals of 0.01 m, and the relevant physical parameters (the detection voltage and temperature) of the measured layer are obtained by a data acquisition instrument. The air–ice and ice–water interfaces are identified, and the ice thickness is then obtained. As shown in Fig. 2, the DS18B20 temperature sensors, which are spaced at equal intervals according to the measurement range, are installed in the detection space.

3. Apparatus components

Fig. 3 shows the schematic of the resistance–temperature (R–T) freshwater ice-thickness apparatus based on R–T synchronous automatic acquisition theory. The apparatus consists of an R–T ice-thickness sensor, a data acquisition instrument, and a remote monitoring center.

The main parameters of the R–T freshwater ice-thickness apparatus are listed in Table 1.

The power consumed during the installation includes the static working current, the working current, the maximum working current, and the GPRS modem online current. Table 2 summarizes the operational time of each working state of the apparatus.

We can estimate the mean working current of the apparatus from Table 2, and it is approximately 0.0114 A, regardless of the change in temperature.

3.1. R–T ice-thickness sensor structure

Fig. 4 shows the structure of the R–T ice-thickness sensor. The left and right dotted boxes represent the sensor barred body and the data acquisition instrument, respectively. The detection and return electrodes are selected and connected to the circuit, as shown in Fig. 1, using a single-chip microcomputer (SCM) program-controlling CPLD and the ADG732 analog multiplexer. The procedure for switching electrodes is as follows. Consider a sensor with a 2-m range, which includes 200 detection electrodes and 32 return electrodes, as an example. The 200 detection electrodes, numbered D1 to D200, are vertically arrayed and embedded on the left side of the barred body's front face from the bottom to the top at intervals of 0.01 m from each other. The 32 return

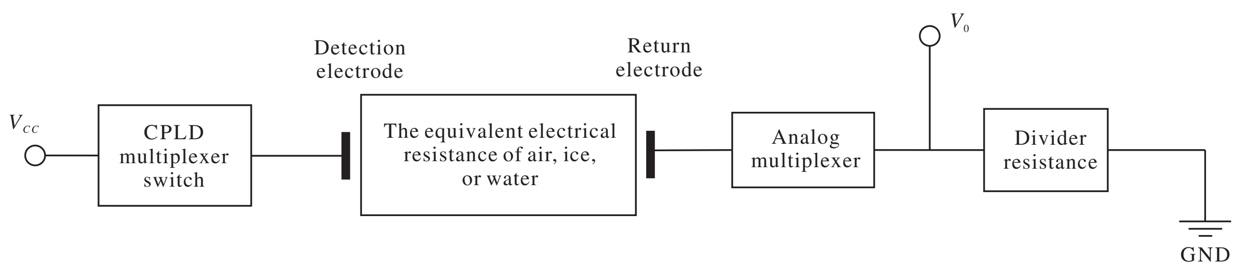

Fig. 1. Block diagram of the equivalent-electrical-resistance detection circuit.