In Field Application of an Innovative Sensor for Monitoring Road and Runway Surfaces

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***Abstract*—Water and ice detection over road and runway surfaces is important to improve traffic safety and to reduce maintenance costs. An innovative low cost capacitive sensor was endowed with an algorithm based on the time derivative of the measured capacitance to indicate the transitions between dry, wet, or icy state of road and runway surfaces. The sensor was investigated theoretically and validated with experiments on field.**

***Keywords*-Capacitive sensor; ice and water detection; road and runway information system.**

I. INTRODUCTION

Investigation of ice formation is important in many different fields, for instance to enhance traffic safety on roads [8], to allert people walking on walkways, to identify the accretion of ice on an aircraft [7], or to control iceberg growing [5].

The detection of water and ice and the assessment of the environmental conditions on road and runway surfaces is attracting increasing attention, as it may significantly contribute to reduce costs for snow and ice control on highways and airports [6]. Indeed, accurate indication on road pavement condition helps agencies to efficiently plan the maintenance (expecially during winter), to reduce wear on the vehicle fleet, to decrease chemical, sand and salt usage, and to provide a better level of service by applying anti-icing practices. The investigation of pavement conditions (dry, wet, or icy condition of the road or runway) supports a weather information system, when integrated with other important data, such as atmospheric measurements (e.g. air temperature and humidity, visibility distance, wind speed and direction, precipitation type and rate, cloud cover, lightning, air quality), water level data (stream, river and lake levels near roads) and other pavement data (temperature, freezing point, chemical concentration).

Many ice detection sensors have been developed, using remote or contact measurements, single point or wide area sensors [3]. Different physical principles can be exploited: mechanical vibrations [2], electro-optics, fiber-optics [13], radio frequency [1], ultrasounds [4].

An innovative ice sensor was introduced in [10] to detect water and ice on exposed surfaces, based on a capacitance measurement. This work is devoted to the investigation of this new ice detection system, using both a mathematical model for the simulation of the system and experimental results recorded in field.

II. METHODS

The state of the pavement is identified investigating the value of the capacitance of an electrode assembly coupled to the road or runway surface. Air, water or ice covering the surface constitutes a layer of dielectric that slightly influences the value of capacitance, which can be measured through a hardware device described below. The problem of assessing the state of the surface from the value of capacitance of the sensor is investigated by a model, which guided the design of a signal processing algorithm for the detection of state transitions. The performances of the sensor were finally assessed with in field experiments.

A. Sensor description

The sensor consists in a capacitance measurement, performed by the device shown in Figure 1A and B. Capacitance is measured at two different frequencies, 200Hz and 20MHz. The sensor consists of a pair of concentric conductive electrodes (with geometry indicated in Figure 1A), which constitute the sensing device, a frequency generator and a charge detector. The electrodes are directly connected to the capacitance measurement circuit, shown in Figure 1C. This circuitry is implemented on a printed circuit board using commercial available low power components. The frequency generator is obtained by a reference voltage source V_R and a controllable switch S_1 to provide different frequencies. The electrode assembly and the material placed over the sensor constitute a capacitor with unknown capacitance C_X. The charge detector comprises a reference capacitor with capacitance C_S that is connected to the electrodes by closing the switch S_2. At the end of the measurement process, the reference capacitor is discharged by closing the switch S_3. In order to increase accuracy in measuring the very small

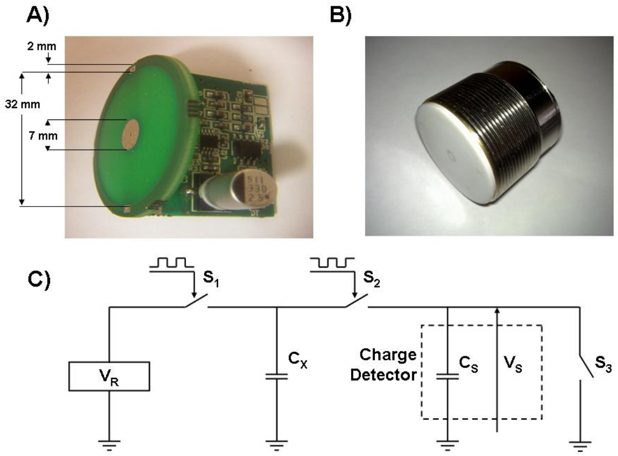

Figure 1. The ice sensor. (A) Picture of the internal electronic circuits. The electrode assembly is located on the top, over the capacitance measurement circuit. (B) Picture of the ice sensor. (C) Schematic layout of the capacitive measurement circuit.

value of capacitance C_X, the sensor was charged and its charge was transferred n times to the reference capacitor before taking a measurement. Therefore the value of the capacitance of the sensor is given by:

$$C_X = \frac{C_S}{n} \frac{V_S}{V_R} \tag{1}$$

where the value of n was chosen to be 50. An automatic calibration procedure is included in the ice sensor to compensate for parasitic capacitances [10]. Also the capacitance of the dry electrode is subtracted by the calibration procedure.

A layer of Arnite was mounted over the sensor electrode, for protection purposes. Arnite was chosen because its dielectric constant is nearly constant within the range of temperature and measurement frequency in which the sensor is used. The sensor was included in a metallic box filled with resin, which protects the circuitry from infiltration of water or chemical agents. The only exposed parts are the Arnite covering the sensor (on the top) and the connector for the power supply of the circuitry and for the connection to a personal computer.

B. Physical concepts

The capacitance of the electrode assembly depends on the geometrical configuration and dimensions of the surfaces of the electrodes, and on the relative permittivity and thickness of the material placed between the electrodes. The relative permittivity, in turn, depends on temperature and measurement frequency [12]. The relation between the relative permittivity of water or ice and measurement frequency is shown in Figure 2 for specific values of temperature. The relative permittivity of ice is substantially constant within a range from DC to about 1kHz, and decreases in the range

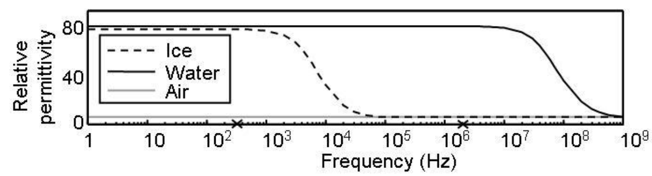

Figure 2. Relative permittivity of water (25°C) and ice (at -10°C) as a function of frequency, with the indication of the two measurement frequencies.

of approximately 2kHz to several hundred kHz. On the other hand, the relative permittivity of water is substantially constant up to approximately 10^9Hz and decreases within the range from 10^9Hz to 10^{10}Hz. The relative permittivity of air can be assumed low and constant for all frequencies.

When measuring the capacitance, distinguishing reliably between water and ice is not possible at low frequencies (lower than 1kHz), but only air can be identified; on the other hand, ice and air cannot be distinguished at high frequencies (between 100kHz and 1GHz), but the presence of water can be identified. Thus, it is possible to distinguish between water, ice and air by two capacitive measurements, at low and high frequencies [10].

C. Mathematical model

The sensor was described using a multilayer electrostatic model (at the maximum measurement frequency the wave length of the electromagnetic field is more than two orders of magnitude greater than the dimensions of the sensor), where three layers were included:

1) dielectric (e.g. the Arnite protecting the sensor) covering the electrodes,
2) air or water or ice placed over the sensor,
3) air.

Each layer was assumed to be isotropic and of constant thickness. The relative permittivities of water and ice were modelled as a function of temperature and frequency [12]. For fixed temperature and measurement frequency, each layer had a constant value of relative permittivity (ε_i). These three layers were positioned over the concentric circular electrodes arrangement. A mixed boundary value problem was studied, imposing opposite value of potential on the two electrodes and vanishing dielectric displacement on the other part of the boundary.

The mathematical problem is symmetrical in cylindrical coordinates, so that it was solved as a function of the radial distance ρ from the centre of the coordinate system and depth z. Finite difference method was used to discretize the domain, which was limited imposing a maximum radius of 30mm. Homogeneous Neumann condition was imposed on such a new boundary. A non-uniform discretization of the domain was used, with increasing resolution close to the electrodes and to the interfaces between different layers.

A linear system of algebraic equations was obtained after discretization. The potential was estimated using Gauss elimination method. Given the potential, the charge q over the internal electrode (which is the same except for the sign as that over the external ring electrode) was estimated as:

$$q = \int_{\rho \le \rho_0,\, z=0} \vec{D} \cdot \hat{n} dS = 2\pi\varepsilon_1 \int_0^{\rho_0} r \frac{\partial \phi}{\partial r} dr \qquad (2)$$

Finally, the capacitance value was obtained as:

$$C = \frac{q}{V_0} \qquad (3)$$

where V_0 is the amplitude of the sinusoidal potential imposed between the electrodes. The capacitance was estimated using the model considering different temperatures, the two measurement frequencies and different states of the sensor. An example of simulated capacitance is shown in Figure 3A. At the beginning of the simulation test, the sensor was dry and at a temperature of 25°C. After 18 samples, the simulated state of the sensor became wet, and the simulated temperature started to decrease up to -20°C with a temperature gradient of -1°C per sample. At 0°C, the simulated state of the sensor was selected as icy. The simulated test continued symmetrically, with the sensor coming back to the dry state at 25°C. The values of capacitance obtained from the model are very close to those obtained by the physical sensors in laboratory conditions [11], or during the in field experiments described below (see Figure 4A and B, after adding a 0.3pF of capacitance of the dry sensor, removed by the calibration procedure described in Section II.A).

D. Algorithm for water, air, and ice detection

An algorithm was developed to discriminate between different states of the sensor (dry, wet, or icy) given the measured capacitance. The values of capacitance obtained at the two measurement frequencies were digitally low-pass filtered (cut-off frequency of 0.002Hz - 100th order causal FIR filter), in order to reduce high frequency variations and instrumentation noise. Transitions of the state of the sensor (dry-wet, wet-icy, icy-wet, and wet-dry) were associated to abrupt variations of the value of capacitance, which were identified using a first-order derivative, as shown in Figure 3B. A jump in the first-order derivative was considered significant if it was higher than a threshold, identified calibrating each sensor before use.

E. In field experiments

A standard sensor and another covered by bitumen (bituminized sensor) were embedded in the pavement of a road to monitor continuously the road surface condition. The bitumen was expected not to affect the measurement, since it has a very small value of relative permittivity and this value

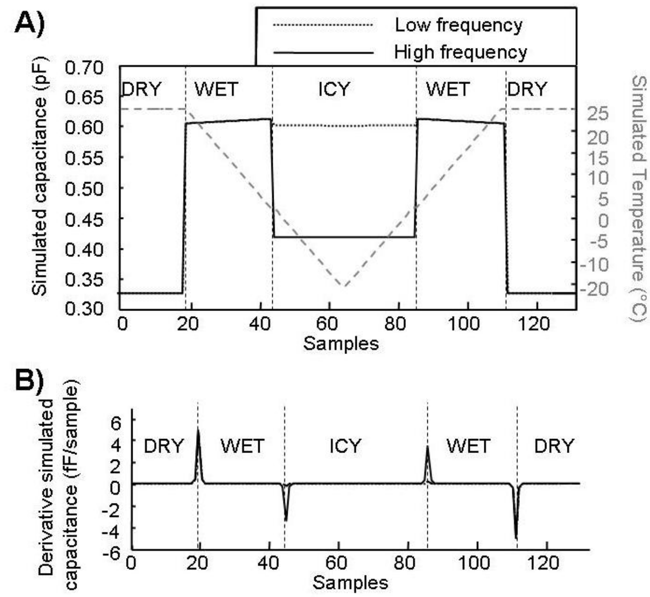

Figure 3. (A) Temperature and simulated capacitance values obtained using the mathematical model for different states of the sensors at different temperatures. (B) States of the sensor revealed by the algorithm.

does not change with the measurement frequency, even if such a layer reduces the sensitivity of the sensor. On the other hand, bitumen provides protection to the sensor and improves the embedding into the road pavement. The sensors were mounted in a secondary street close to the runway at the Turin-Caselle airport. Moreover, a complete weather station (PCE Group - PCE FWS-20) was mounted close to the sensors to monitor meteorological variables (humidity, temperature, pressure, quantity of rain falls, velocity and direction of the wind). Sensors were monitored over a 36 days period.

III. Results

Values of capacitance (raw data) and estimated sensor states are shown in Figure 4 for a standard and a bituminized sensor (high and low measurement frequencies) during the in field test at the Turin-Caselle airport, over the period 12/01/10 - 17/02/10. Meteorological data obtained by the weather station are also included in Figure 4D (quantity of rain falls), 4E (air humidity) and 4F (ambient temperature).

Both sensors revealed different conditions (dry, wet, or icy), since the state of the road surface continuously changed. Wet state of the sensor surface was estimated during rainy or high humidity conditions. Transition to icy conditions were identified when the sensor was wet and temperature decreased to a negative value.

The in field experiments showed equivalent precision on the identification of the state of the surface of the road for both standard and bituminized sensors. The wet condition after raining lasted longer for the bituminized sensor, probably

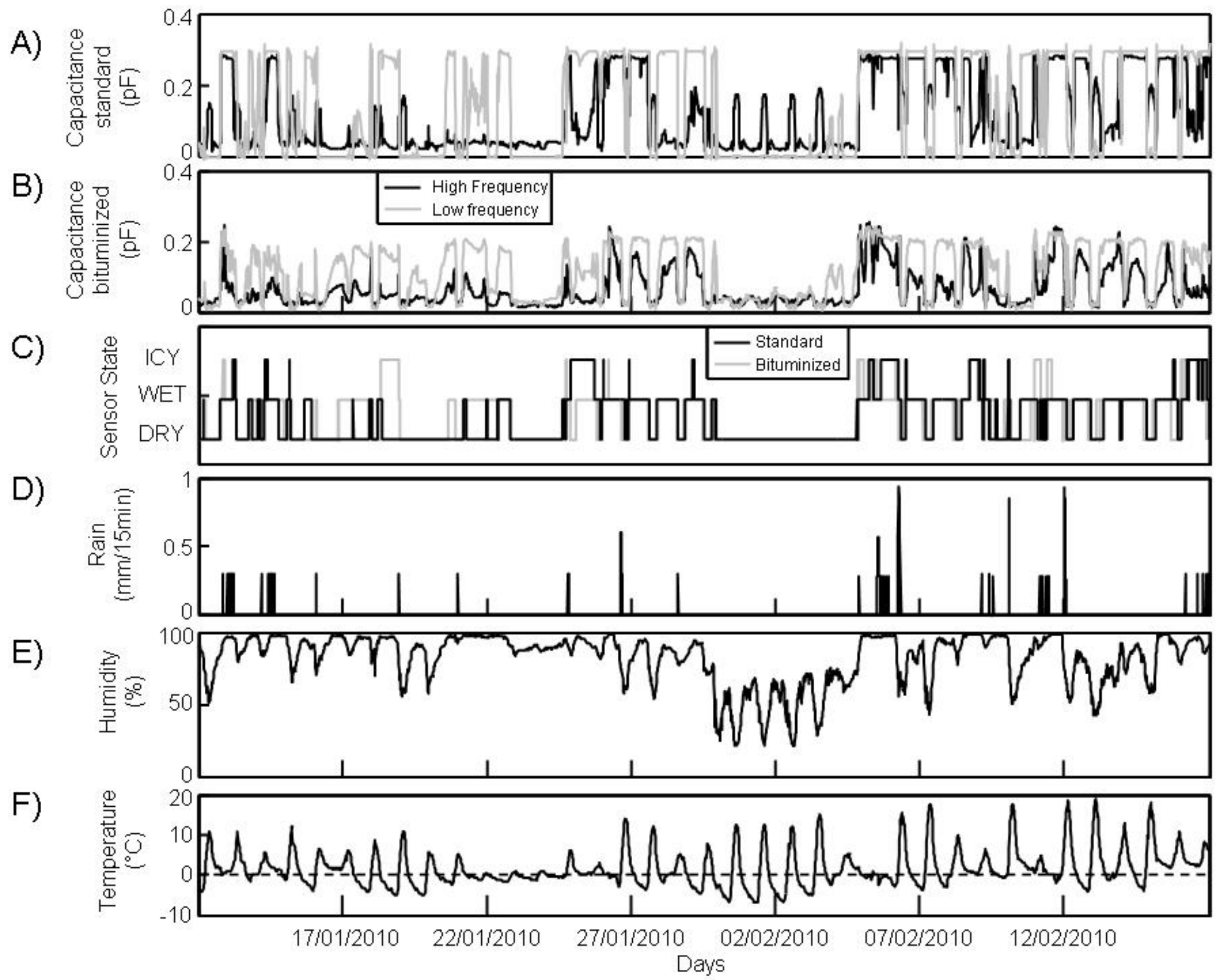

Figure 4. Results of the in field experiments obtained from the sensors placed at the Turin-Caselle airport over the period 12/01/2010 - 17/02/2010. (A) Values of capacitance (raw data) at both frequencies obtained for the standard sensor. (B) Values of capacitance (raw data) at both frequencies obtained for the bituminized sensor. (C) States of the sensors revealed by the algorithm. (D) Quantity of rain falls. (E) Ambient humidity. (F) Ambient temperature.

due to the porosity of bitumen which determines a delayed drying with respect to the standard sensor. Wet condition of the surface of the runway was identified also in the case of fog, confirming that even a slow condensation of water over the sensor surface is associated to a jump in the value of capacitance that may be easily identified.

IV. Conclusion

A low cost capacitive sensor for the assessment of road pavement conditions is investigated. Reliability of the estimates provided by the sensor were assessed in laboratory conditions in [11]. The mathematical model of the sensor allows characterizing and simulating the sensor in different conditions. The simulated values of capacitance obtained using the mathematical model confirm the accuracy of the measurements carried out in laboratory conditions. Nine sensors were placed in a climatic chamber in the same conditions [11]. The estimates of the state of the sensors and the timing of the identification of wet-icy or icy-wet transitions were studied. Reliable estimates were obtained by all sensors, with a dispersion of the transition times of the order of a few minutes.

Nevertheless, the capacitance of the sensor in field conditions may depend on many unpredictable factors which cannot be simulated in the laboratory. For example, different values of humidity and temperature, the presence of fog, snow or possible contaminations covering the surface of the sensor (e.g. dirt, fuel or salt) may affect the value of capacitance. This work assesses the reliability of the sensor in field conditions, indicating that the estimated state of the sensor surface is in line with meteorological data. Moreover, bituminized and standard sensors are compared.

As confirmed by simulations, one effect of bitumen is a reduction of the sensibility of the sensor of the order of 30%. Nevertheless, in field experiments indicate that the estimation of the state of the pavement conditions are not compromized by the presence of bitumen, which is suggested as the bituminized sensor is more robust and better integrated to the pavement with respect to the standard sensor.

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