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Sensitivity of capacitive throughput sensor to the change of material relative permittivity

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Abstract. The capacitive throughput sensors have been tested in many applications (e.g. the throughput measurement of potatoes, sugar beet, chopped maize and hops). The results showed that the capacitive throughput sensors can be very perspective in some cases. The capacitive sensor for the throughput measurement can be described as a parallel plate capacitor where the dielectric is a mixture of air and the measured material. The equivalent dielectric constant increases with the increasing thickness of the material layer between the plates and the electric capacitance of the capacitor is increasing as well. The thickness of the material layer between the plates can be then determined via the electrical capacitance measurement. The main goal of this work is to describe the relationship between the relative permittivity of the material and the sensor output. The sensor values output directly depend on the sensor impedance and it is influenced by the electric field between the electrodes. The electric field is most influenced by the dielectric properties of the material and the distribution of the material. It was found that the influence of the relative permittivity change is significant only for less values (approximately 10 and less). These results mean that the material with the higher relative permittivity is useful for the capacitive throughput sensor. Also this behaviour can explain why the influence of the moisture is less significant for the moister material, because moister materials have higher relative permittivity.

Key words: capacitive throughput sensor, relative permittivity, moisture content.

INTRODUCTION

The material throughput measurement during the harvest is an important requirement of yield maps creating. However, the data obtained from these sensors can be used in other cases (e.g. an optimization of the material transport). Many yield sensors based on different principles were successfully tested for the combinable crops (Reinke et al., 2011; Reyns et al., 2002). Only few yield measurement systems are available for the non-combinable crops (Kumhála et al., 2009) and the research still continue in this area (Jadhav et al., 2014).

The capacitive throughput sensors have been tested in many applications. The Capacitive throughput sensor can be described as a parallel plate capacitor where the dielectric is the mixture of air and the measured material. The Equivalent dielectric constant increases with increasing thickness of the material layer between the plates. The thickness of the material layer between the plates can be then determined via the electrical capacitance measurement.

One of the earliest papers about the throughput measurement with the capacitive sensor was published by Stafford et al. (1996). Authors used the capacitive sensor to determine the grain mass flow. Other works were presented by Martel and Savoie (1999) and Savoie et al. (2002). Both papers deal with the measurement mass flow rate through a forage harvester. The testing of capacitive throughput sensors for potatoes, sugar beet, chopped maize and hops was presented in other papers (Kumhála et al., 2009; Kumhála et al., 2010; Kumhála et al., 2013).

The sensors based on capacitance measurement are commonly used for the moisture content determination because the dielectric properties of materials are highly correlated with the moisture content of the material (Nelson & Trabelsi, 2012). Many authors wrote about the techniques for the moisture content measurement (e.q. de Loor, 1983; Eubanks & Birrell, 2001; Lawrence, et al., 2001; Paz et al., 2011).

Stafford et al. (1996) presented that the capacitive throughput sensor is sensitive to the moisture content and this effect can be compensated by measuring of the capacitance at two widely spaced frequencies. However, authors state on the base of their measurement that the sensor output was much less sensitive to the moisture content than anticipated. Savoie et al. (2002) presented that their system was better correlated with the water flow rate ($R^2 = 0.624$) than with the wet mass–flow rate ($R^2 = 0.468$). Kumhála et al., 2010 performed a measurement where the influence of the moisture content was tested. The measurement was performed with four balsa blocks which were moistened to about 80% of moisture content and then slowly dried. Authors presented that the sensor was not sensitive to the change of the moisture content when the material moisture content of balsa bock varied from above 75% to 65%. However, in the case when materials with lower material moisture content are measured, the changes in the material moisture content itself can influence the results of the capacitive throughput measurement.

The main goal of this work is to describe the relationship between the relative permittivity of the material and the sensor output. If the electrostatic field in the sensor sensing area is assumed (Lev et al., 2013) the most important material parameter is the relative permittivity. Kumhála et al. (2010) presented interest results. However a theoretical rationale is missing.

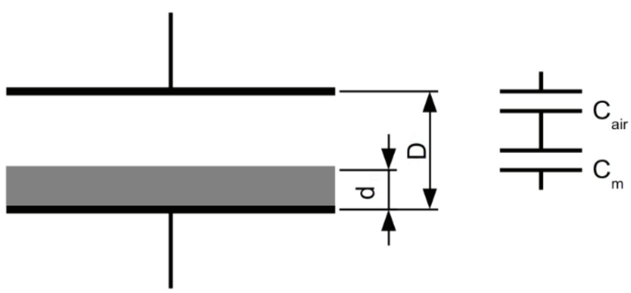

Figure 1. The diagram of the capacitive throughput sensor: *D* – the distance between electrodes; *d* – the thickness of the material layer, C_{air}; C_m – the capacitance of the substituted capacitors.

MATERIALS AND METHODS

In many cases the capacitive throughput sensor can be described by two parallel plate capacitors connected serially and with a different dielectric material (Kumhála et al., 2009). The first capacitor (C_m) represents the measured material and the second capacitor (C_{air}) represents the air above the measured material. The diagram of the sensor is in Fig. 1.

The total capacitance of the sensor can be calculated by this flowing equation:

$$C_T = \frac{C_{air} C_m}{C_{air} + C_m} = \frac{S \varepsilon_m \varepsilon_{air} \varepsilon_0}{d(\varepsilon_{air} - \varepsilon_m) + \varepsilon_m D} \tag{1}$$

where: C_T – total electrical capacitance of the sensor; F; S – sensor plate area, m^2; ε_m –relative permittivity of the measured material; ε_{air} – relative permittivity of the air; ε_0 – permittivity of vacuum; ε_0 = 8.85 10^{-12} F m^{-1}; d – thickness of material layer, m; D – distance between electrodes, m.

The impedance magnitude of the sensor equals the capacitive reactance and it can be calculated:

$$X = \frac{1}{\omega C_T} = \frac{d(\varepsilon_{air} - \varepsilon_m)}{S \varepsilon_m \varepsilon_{air} \varepsilon_0 \omega} + \frac{D}{S \varepsilon_{air} \varepsilon_0 \omega} = dA + X_E \tag{2}$$

where: X – capacitive reactance of the sensor; Ω; ω – angular frequency, rad·s^{-1}; A – constant of the sensor; X_E – capacitive reactance of the empty sensor, Ω.

The equation (2) is a linear equation. The constant A is negative because ε_m is always higher than ε_{air}. The positive capacitive reactance change magnitude of the sensor is:

$$X_{ch} = -dA = \frac{d(\varepsilon_m - \varepsilon_{air})}{S \varepsilon_m \varepsilon_{air} \varepsilon_0 \omega} \tag{3}$$

where: X_{ch} – capacitive reactance change magnitude of the sensor, Ω.

The influence of the material relative permittivity change can be expressed as the error of the capacitive reactance change:

$$\Delta Xch = \frac{d(\varepsilon_m (1+\mu) - \varepsilon_{air})}{S \varepsilon_m (1+\mu) \varepsilon_{air} \varepsilon_0 \omega} - \frac{d(\varepsilon_m - \varepsilon_{air})}{S \varepsilon_m \varepsilon_{air} \varepsilon_0 \omega} = \frac{d\mu}{S \varepsilon_m \varepsilon_0 \omega (1+\mu)} \tag{4}$$

where: ΔX_{ch} – the influence of a material relative permittivity change, Ω; μ – a relative change of a material relative permittivity.

The relative error of the capacitive reactance change is:

$$\delta = \frac{\Delta X_{ch}}{X_{ch}} 100 = \frac{\mu \varepsilon_{air}}{(\varepsilon_m - \varepsilon_{air})(1-\mu)} 100 \tag{5}$$

where: δ – relative error of the capacitive reactance change, %.

RESULTS AND DISCUSSION

The dependence between the capacitive reactance of the sensor and the material thickness layer was calculated based on the equation (2) and it is shown in Fig. 2. All values were calculated for: $\omega = 2\pi f$, where $f = 1$ MHz, $\varepsilon_{air} = 1$, $S = 1$ m^2 and $D = 1$ m. In the Fig. 2 there are five lines and each of them represents different relative permittivity of the measured material. All lines begin at the capacitive reactance value $X = 112$ kΩ where the sensor was without measured material. If the material thickness layer is $d = 1$ m, the sensor is wholly filled by the measured material. It is evident from Fig. 2 that the capacitive reactance of the sensor is significantly influenced by the relative permittivity, if the sensor is wholly filled by the material. Also it can be state that the influence of the relative permittivity increases with the increasing thickness of the material layer. However, the output values of the capacitive throughput sensor usually depend on the capacitive reactance change magnitude of the sensor (Kumhála et al., 2009; Lev et al., 2013) and these values are much less sensitive to the relative permittivity change of the measured material.

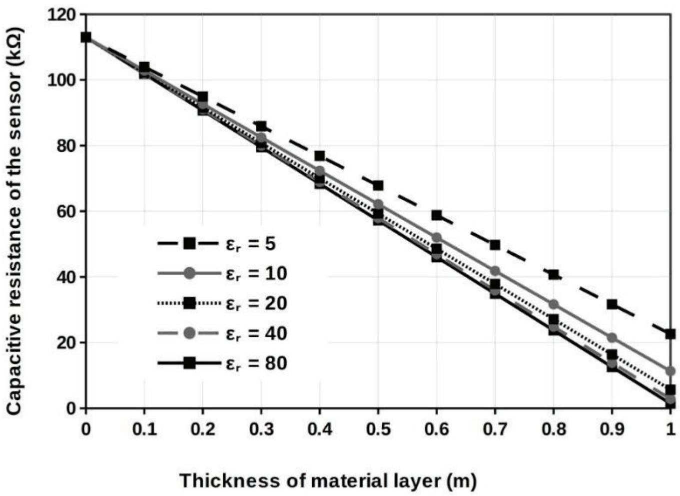

Figure 2. The dependence between the capacitive reactance of the sensor and the material thickness layer.

The equation (5) represents the relative error of the sensor capacitive reactance change. It is evident from this equation that the relative error of the sensor capacitive reactance change depends on the relative change of the material relative permittivity and on the relative permittivity of the measured material only. The relationship between the relative error of the capacitive reactance change and the relative permittivity of the measured material is shown in Fig. 3. In the Fig. 3 there are six curves and each of them represents different relative change of the material relative permittivity μ. The values were chosen: μ = -0.5, -0.2, -0.1, 0.1, 0.2, 0.5. The negative or positive value means that the relative permittivity was decreased or increased, respectively.

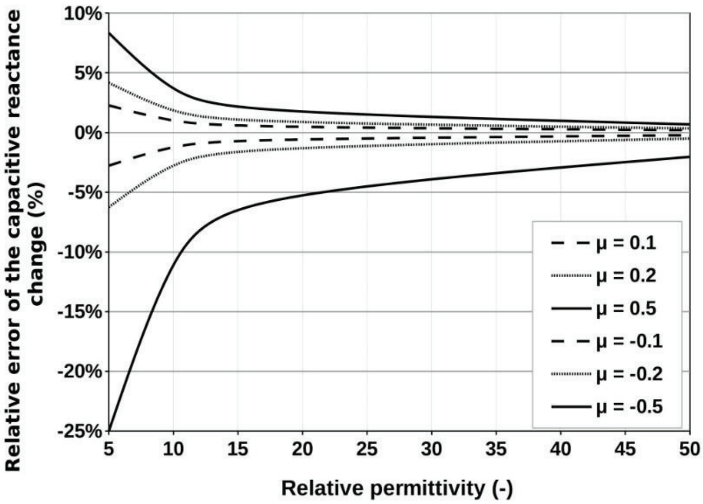

Figure 3. The relationship between the relative error of the capacitive reactance change and the relative permittivity of the measured material.

It can be seen in the Fig. 3 that the relative error of the sensor capacitive reactance change is decreasing very quickly with the increasing relative permittivity. If the relative permittivity of the measured material is for example 10 and μ = 0.5 (the relative permittivity increases to 15) the relative error of the capacitive reactance change is only about 4%. The negative or positive value of the relative error means that the relative error was caused by negative or positive relative change of the relative permittivity, respectively. It is logical that if the change of the relative permittivity is negative, the absolute value of the relative error of the sensor capacitive reactance change is bigger.

It is apparent that the influence of the relative permittivity change is more significant for small values. These results correspond with the paper of Kumhála et al. (2010) and they explain that behaviour. Savoie et al. (2002) presented different results. Nevertheless, their measurement method was quite different. Authors used the capacitance controlled oscillator and the output of their device directly depended on the sensor capacitance (not the capacitance/capacitive reactance change). Also it should be taken into account that the material distribution in their throughput sensor was fully random and the model presented in this paper would probably not be valid in that case.

CONCLUSIONS

The sensitivity of the capacitive throughput sensor to the change of the material relative permittivity was studied in this paper. The mathematical model presented in this study is simple but it accords with previous works (Stafford et al., 1996; Kumhála et al., 2009; Kumhála et al., 2010) and it was not presented before. Results show that the influence of the capacitive throughput sensor on the change of the material relative permittivity is very quickly decreasing with the increasing relative permittivity. These results mean that materials with higher relative permittivity are useful for capacitive throughput sensors. Also the influence of the moisture is less significant for moister material, because moister materials have higher relative permittivity.

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