Computers and Electronics in Agriculture 136 (2017) 210–220

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

Original papers

Industrial scale electromagnetic grain bin monitoring

Colin Gilmore [a], Mohammad Asefi [b], Jitendra Paliwal [c], Joe LoVetri [b,*]

[a] 151 Research Inc., Winnipeg, MB R2J 1K4, Canada
[b] Department of Electrical and Computer Engineering, Room E2-390 EITC Building, University of Manitoba, 75 Chancellor's Circle, Winnipeg, MB R3T 5V6, Canada
[c] Department of Biosystems Engineering, Room E2-376 EITC Building, University of Manitoba, 75 Chancellor's Circle, Winnipeg, MB R3T 2N2, Canada

ARTICLE INFO

Article history:
Received 9 June 2016
Received in revised form 11 February 2017
Accepted 9 March 2017
Available online 23 March 2017

Keywords:
Grain bin imaging
Grain spoilage
Electromagnetic imaging
Grain bin monitoring
Three-dimensional imaging

ABSTRACT

We present an Electromagnetic Imaging (EMI) system capable of detecting spoiled grain regions inside a large-scale grain storage bin. Stored grain represents significant economic and nutritional value to humankind, but despite this value, storage losses are common (estimated to vary from 2% to 30%). While there are many mechanisms that cause storage losses, virtually all of them involve higher temperature and/or moisture content of the stored grain. Increases in temperature and/or moisture both raise the complex permittivity of the grain. Our EMI system creates a 3D image of the complex permittivity through 24 antennas mounted on the side of the bin operating at a frequency of 93 MHz, combined with a 3D Finite-Element inversion/imaging code.

The antennas are designed to have both the desired electrical characteristics, as well as withstand the significant forces caused by the loading and unloading of the grain. Results with 55 tonnes of hard-red winter wheat in a ≈2500 bushel (80 tonne) bin show that our system is capable of detecting a small spoilage region (0.24% of total grain volume, 2/5 of a wavelength in size) inside dry bulk grain. The 3D EMI system is a viable method of detecting spoiled grain in industrial grain storage facilities.

1. Introduction

The vast majority of the world's food energy comes from a small number of staple crops which are harvested and then stored for later use. Storage times can vary from several weeks to many years. Due to the extreme importance of these crops to humanity's food supply, their safe storage is critical. Even with this importance, estimates of storage losses vary from 2% to 30% (Sinha, 1995; Muir and White, 2000), and these losses lead to economic costs estimated to be hundreds of millions of dollars in Canada alone (Jayas et al., 2011).

There are numerous threats to the quality and quantity of stored grain: the seeds may germinate while in storage, molds and fungi may grow, insect infestations may occur, or grain be eaten by rodents and other animals. For modern faclities with sealed storage bins or silos, the most important parameters of safe grain storage are the moisture content and temperature of the stored grain (FAO, 2011). High moisture content of stored grain leads to germination, mold/fungus growth, attracts insects, and also prevents the respiration of the grain (which is necessary for safe storage). Temperature is also an important parameter for safe storage of grain as low temperatures reduce the probability of early germination, as well as reducing the metabolic rates or even killing insects and molds/fungi.

Both high moisture content and high temperatures may be a cause of, and a result of spoilage. High temperatures and moisture create conditions conducive to sprouting and to mold and fungus growth; while sprouting, infestations of insects, and mold growth create heat and moisture through biochemical processes (Sinha, 1995). High temperature and moisture in stored grain is part of a positive feedback process, where high values in some spots create conditions for further spoilage, raising temperatures and moisture even further. Thus, for safe storage it is important that both moisture content and temperature be brought to, and kept at, low levels. For safe storage, these levels should also be monitored. The particular moisture/temperature level that may be considered safe depends on grain type, external conditions, and expected storage time (FAO, 2011). An example of safe storage moisture/temperatures is shown in Fig. 1. Most grains are harvested at moisture contents and temperatures that are not safe for long term storage (i.e. grain must be dried or conditioned before it may be stored safely).

Farmers and grain handlers use a variety of systems to ensure that stored grain is brought to optimal storage conditions after harvest and these conditions are maintained through the duration of

* Corresponding author.
E-mail addresses: cgilmore@151research.com (C. Gilmore), asefim@myumanitoba.ca (M. Asefi), j.paliwal@umanitoba.ca (J. Paliwal), Joe.LoVetri@umanitoba.ca (J. LoVetri).

http://dx.doi.org/10.1016/j.compag.2017.03.005
0168-1699/

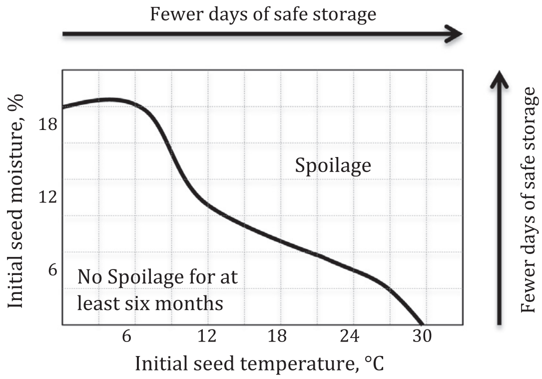

Fig. 1. An example of grain storage outcomes for wheat with varying moisture and temperatures. Modified from White (2002).

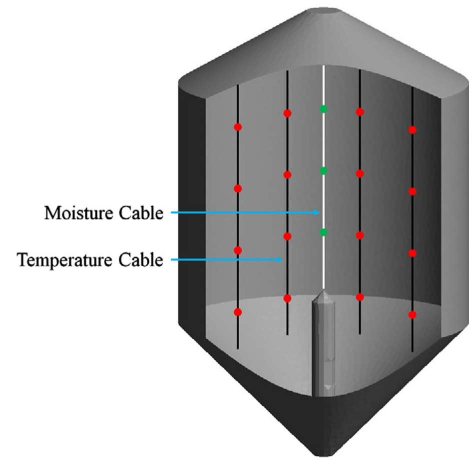

Fig. 2. A typical temperature and moisture grain monitoring system. Cables are suspended from a necessarily reinforced ceiling. Sensors are spaced approximately 1.2 m apart along each cable and are locally sensitive.

storage. These systems vary in sophistication from simply opening the top of the bin and smelling to detect moisture, mold and fungi, point sensing systems to measure moisture content of grain samples (Maier et al., 2010), temperature and moisture sensors (e.g., Folk, 2016), to chemical sensors designed to detect insect respiration products (Maier et al., 2010). Entering bins is time consuming, dangerous (Freeman et al., 1998), and not a reliable method of detecting poor storage conditions. The most common method of monitoring storage conditions is the use of a series of temperature/humidity sensors attached to cables hung from the storage bin's roof. An example of such a system is shown in Fig. 2. In such a system, point sensors measure the local temperature and humidity approximately every 1.2 m along the cable. These cable measurement systems require strengthening the roof of the bin, only sense the conditions local to each sensor, and as grain is an excellent thermal insulator, grain hot-spots (i.e. spoilage regions where the temperature has risen) can occur without detection for long periods of time (White, 2000).

In Asefi et al. (2015), we introduced the concept of monitoring the entire contents of a storage bin through the use of Electromagnetic Imaging (EMI). While many different imaging methods could be broadly construed as electromagnetic (e.g. human sight, radar, x-rays, MRI), we use EMI as a more restrictive term: by EMI, we mean the use of electromagnetic radiation to create images of materials through the use of multiple transmitting and receiving antennas, with images generated via a non-linear optimization algorithm. This is an example of an inverse scattering problem. EMI in this sense has a wide range of applications: from deep sea oil and other geophsyical prospecting (Yang et al., 2013; Abubakar et al., 2011), medical imaging (Meaney et al., 2000, 2013, 2012,, 2010, 2008), pipe-contents monitoring (Mallach et al., 2016), and more (Litman and Crocco, 2009; Joachimowicz et al., 1991; Rocca et al., 2009; Di Donato et al., 2015). Frequencies of operations vary from less than 1 Hz to the 10's of GHz range. In EMI, two simultaneous 3D images are made: one of the electrical permittivity of the contents, and another of the electrical conductivity. The permittivty relates to the speed of light in each voxel of the image, while the conductivity relates to the loss of electromagnetic energy in that voxel. These two parameters are typically combined into the complex permittivity:

$$\epsilon(\vec{r}) = \epsilon_0\epsilon_r(\vec{r}) = \epsilon_0(\epsilon'(\vec{r}) - j\epsilon''(\vec{r})) = \epsilon_0\left(\epsilon'(\vec{r}) - j\frac{\sigma_{eff}(\vec{r})}{\omega\epsilon_0}\right) \tag{1}$$

where $\vec{r}$ is the 3D position vector, $\omega = 2\pi f$ is the angular frequency, σ_{eff} is the effective conductivity, ϵ_0 is the permittivity of free space, and $\epsilon_r = \epsilon' - j\epsilon''$ is the relative complex permittivity, henceforth referred to as the complex permittivity (or sometimes simplified to permittivity). In general, both ϵ' and σ_{eff} vary with frequency.

Electromagnetic methods of measuring grain have a long history. The fundamental reason is that grain moisture content can be inferred by measuring the bulk permittivity and conductivity, as well as the temperature of the grain, e.g. Nelson and Stetson (1976), Nelson (2008) and Nelson et al. (2000). Measurement systems consist of point systems (Nelson and Trabelsi, 2006), as well as flow-though systems (Kraszewski et al., 1998). It is important to note that inferring both the temperature and moisture content of grain simultaneously from knowledge of the complex permittivity may not be possible: there are multiple temperature/permittivity profiles that can give rise to the same complex permittivity (Nelson et al., 2000). However, for the purposes of safe storage, both high temperatures and high moisture content cause complex permittivity to rise (Nelson et al., 2000; Nelson, 2008), and most spoilage mechanisms cause both high temperatures and high moisture content (Nelson and Trabelsi, 2006).

Simply put, high permittivity and conductivity indicates spoilage (or unsafe storage conditions) of grain. Any system which can detect rises in either temperature or moisture (or both) is capable of detecting unsafe grain storage conditions.

1.1. Contributions

Within this work, we present an industrial-scale EMI imaging system and set of sensors that are an evolution of previous small-scale/lab-based imaging systems (Asefi et al., 2015; Asefi et al., 2016). The goal of this new system is to scale previous work to realistic industrial dimensions, develop a viable protocol for imaging the whole bin without complicated lab-based measurements, and prove that small regions of spoilage can be detected via this system. Specific contributions of this work include:

1. Presentation of the first industrially viable EMI imaging system for whole-bin imaging.
2. Detection and imaging of realistic grain spoilage spots.
3. Design of a set of vertically oriented antennas/sensors which are bolted to the bin wall, and have been carefully designed to withstand the extreme forces generated during bin loading/unloading procedures.
4. Avoiding the use of a direct measurement system to determine the initial permittivity of the stored grain. It is instead estimated from the prior information of the initial grain moisture content (which is commonly measured by farmers and grain handlers prior to storage).