STATE OF THE ART
OF
CAPACITIVE TOMOGRAPHY
FOR THE LOCATION OF PLASTIC PIPING

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STATE OF THE ART & SYNOPSIS OF AVAILABLE LITERATURE

1.0 INTRODUCTION

The objective of this synopsis is to provide a general overview of the current state of the field of capacitive tomography. This will accomplish two objectives. The first objective being a theoretical and experimental grounding of the proposed capacitive tomography project. The second objective being to indicate or provide justification for the need to conduct further research into the particular area of underground detection of non-metallic structures by the use of electric fields.

The field of capacitive tomography is currently undergoing significant evolution. Consequently there is a considerable body of literature pertaining to this field. This document will give a cross section of the available literature and patents regarding capacitive tomography as related to the current project. No attempt is being made to provide an exhaustive listing of all of the current literature on capacitive tomography, rather a listing of literature which will provide a good understanding of the current state of the field as it pertains to this particular project.

Capacitive tomography is the detection of the structural details of an object by monitoring changes in an electric field produced by that object. The electric field most often will be produced by an arrangement of capacitive elements. In the current capacitive tomography project a number of electric field producing and electric field detection elements are configured in a planar array. The field producing elements or transmission elements will be driven by a *50-200* kHz signal. The planar array will be placed directly on or proximate to the surface of the ground. The goal of this system is to detect natural gas pipe structures in particular those that are composed of non-metallic materials, such as plastic or ceramic pipe.

2.0 OVERVIEW OF TECHNIQUES

A capacitor is a physical device that stores energy in the form of an electric field. The electric field that stores this energy may be time dependant or time independent. The type of physical structure that may be used to generate the electric field is typically, but not necessarily an arrangement of metallic plates.

2.1 The use of time dependant electric fields gives rise to the question of when the detection scheme under consideration would more aptly be understood as a RF antenna problem rather than a capacitor problem. This question arguably has more heuristic value than practical value.

Strictly speaking capacitive tomography should be defined as the detection, sensing, or imaging of physical structures by the detection and analysis of variations or perturbations in the electric field parameters. These changes in the electric field parameters results from changes in the electrical permitivities of the physical structures that reside in the physical space that is being sensed. Thus there should be negligible self interference of the electromagnetic field brought about by the physical dimensions of the capacitor elements that is generating the electrical fields. This would imply that the size of the capacitor plates and the distances between the plates and the structures to be detected would be very small compared to the wavelength of the electric fields.

A narrow definition of the field of capacitive tomography should not include those detection schemes where wave associated phenomenon such as interference (constructive and destructive), reflection, diffraction, etc., is the primary means by which information about subsurface structures are derived. None the less there is enough correlation between wave scattering detection and capacitive field detection schemes such that valuable insight and perspective can be gained by citing representative tomographic studies that are arguably not strictly capacitive in nature. Thus a number of the papers and patents cited in the following pages will not be purely capacitive in nature, some will have elements of both wave and capacitive elements. Consequently papers will be cited where the time dependent electromagnetic wave properties of the detection scheme will be utilized.

3.0 CATALOG OF CITED LITERATURE

There are a considerable number of papers and patents directly addressing the field of subsurface imaging. Of these the ones utilizing the electromagnetic spectrum as the medium of energy transmission predominate. The majority of subsurface imaging techniques utilizing the electromagnetic spectrum fall into the following categories, high frequency radar imaging, low to medium frequency wave dispersion and analysis, and low frequency capacitive dielectric perturbation analysis. The following citations will address the last two categories and will omit subsurface radar imaging techniques.

3.1 LOW TO MEDIUM FREQUENCY ELECTROMAGNETIC FIELD IMAGING TECHNIQUES

In “Method for Imaging with Low Frequency Electromagnetic Fields” US patent 5,373,443, dated December 13, 1994 inventors Lee Ki H. (Lafayette, CA) and Xie Gan Q. (Berkeley, CA) have developed a imaging technique using low frequency electromagnetic waves generated from one or more spatially distributed transmitters, placed in holes in the ground. Several receivers are spatially dispersed to collect the reflected electromagnetic energy. Wavefield transforms and ray tomography are used to give high resolution imaging of electrical conductivity.

In “Method and Apparatus for Transmitting Electromagnetic Signals into the Earth from a Capacitor” US patent 5,192,952 dated March 9, 1993 inventor Johler J. Ralph has proposed that a short pulse of voltage can be applied to a capacitor in direct contact with the earth. This transmits a wide spectrum pulse of electromagnetic energy into the earth. A fraction of the transmitted energy is reflected from subsurface layers, which are then processed to give an image. The size of the capacitor, d, is very much less than the wavelength of the electromagnetic pulse. Electromagnetic frequencies of between 1MHz and 100MHz are utilized for transmission, frequencies in the range of 500 KHz and 25 MHz are received and analyzed to determine sub-surface structural detail. This method of sub-surface imaging yields structural detail from tens to hundreds of feet in depth. It relies on the reflection and transmission properties of physical structures to yield meaningful data.

In “System and method for earth probing with deep sub-surface penetration using low frequency electromagnetic signals”, US patent 5,357,253 dated October 18 1994, inventor Paul Van Etten, uses burst of RF energy of less than 3 MHz to image subsurface physical structures from tens to hundreds of feet deep. The proposed invention provides for the removing of system distortions, compensating of aliasing errors, frequency dependent antenna gain, and phase variations.

3.2 CAPACITIVE SENSING AND IMAGING

In a patent entitled “ Driven Shielding Capacitive Proximity Sensor”, patent number 5,166,679, dated November 24, 1992, inventors John M. Vranish and Robert L. McConnell have presented an invention for a capacitive proximity sensor that will detect the intrusion of a foreign object into the working space of an electrically grounded robotic arm. The capacitive proximity-sensing element is backed by a reflector that is driven by an electrical signal of the same amplitude and phase as that signal which is detected by the sensor. It is claimed that by driving the reflector plate with the same signal that is on the sense element significant increases in the sensor's range and sensitivity are accomplished.

In a patent entitled “Steering Capaciflector Sensor”, patent number 5,363,051, dated November 8, 1994, inventors Del T. Jenstrom and Robert L. McConnell, present an invention that will allow for the steering of the electric field lines produced by a capacitive type proximity sensor. The inventors assert the claim that by steering or focusing the electric field will allow an increased ability to discriminate and determine the range of an object in the area of observation over that of previous capacitive sensors. Differential voltages applied to shielding plates spatially arranged around the sensor plate accomplish steering of the electric field lines.

In a patent entitled “Buried Pipe Locator Utilizing A Change In Ground Capacitance”, patent number 5,617,031 dated April 1, 1997 inventor John E. B. Tuttle has invented a portable buried pipe detection device that utilizes changes in the electrical properties of the soils surrounding underground pipes. The detection method consists of the injection of a low frequency sinusoidal wave into the ground via an array of injector/sensor plates. Subsequent modification of the injected signal by variations in ground impedances brought about by the existence of buried piping structures will result. The modified signals will be detected by the spatially separated sensor elements located on the device. The injector/sensor elements are constructed in such a manner as to comprise a capacitive bridge circuit when viewed in conjunction with the ground. As the detection array is moved along the ground any occurence of underground piping structures will imbalance the capacitive bridge and give rise to a detectable electrical signal.

In a patent entitled " Magnetometer with Waveform shaping" patent number 6, 144,206 dated November 7, 2000, inventor Neil J. Goldfine has invented a portable device to locate and discriminate metallic or non-metallic land mines. This device utilizes a magnetometer sensor to detect those mines with a significant metallic composition and a capacitive sensor array termed a "dielectrometer" to detect non-metallic mines. The inventor describes several possible spatial configurations for the arrangement of the sensor elements in the dielectrometer. The first example given is a pair of interdigitated electrodes, a sinusoidal voltage drives one of the electrodes and the other is connected to a high impedance buffer. The depth of sensitivity is determined by the electrode spacing. Another arrangement specified by the inventor is an array of elements interleaved with a continuous interdigitated electrode. This arrangement allows for potential of constructing a two dimensional image of the horizontal subsurface ground plane.

APPENDIX

Selected Technical Papers on Electrical Capacitance Tomography

The following is a selection of selected papers describing the design, operation and application of electrical capacitance tomography systems. We have put a few brief comments next to each title to indicate the relevant content of each paper.

1. Design of ECT Systems

- "Tomographic imaging of two-component flow using capacitance sensors". Huang, Plaskowski, Xie and Beck, J.Phys E: Sci Instrum.22 (1989) pp173-177.
  Comments: The first full description of the UMIST ECT system, on which PTL300 ECT systems are based. Contains a description of the LBP algorithm image reconstruction algorithm, based on the use of binary sensitivity maps
- UK Patent GB 2214640B "Tomographic flow imaging system" 20-01-1988
  Comments: Patent describing the UMIST ECT system
- "Capacitance-based tomographic flow imaging system", Huang, Plaskowski, Xie and Beck, Electronics Letters 31st March 1988 Vol 24 No 7 pp 418-419.
  Comments: Description of the ECT system with particular reference to the measured sensitivity distribution between electrode-pairs
- "Recent developments and industrial/research applications of capacitance tomography", Reinecke and Mewes, Meas Sci. Technol 7 (1996), pp 233-245.
  Comments: A good review of ECT technology up to 1996, with a particularly comprehensive set of references.
- "Electrical capacitance tomography with square sensor", Yang and Liu, Electronics Letters, 18th February 1999, Vol. 35, no. 4, pp 1-2
  Comments: Describes how ECT can be applied for use with a square sensor and describes and gives results from the use of iterative techniques to improve the image accuracy.
- "Design of sensor electronics for electrical capacitance tomography". Huang, Xie, Thorn, Snowden and Beck, IEE Proceedings-G, Vol. 139, no. 1, February 1992 pp 83-88.
  Comments: Describes the design, characteristics and performance of the UMIST ECT system.
- "Process tomography: a European innovation and its applications", Beck and Williams, Meas. Sci. Technol., 7, (1996), pp 215-224.
  Comments: Review paper on electrical tomography with specific references to ECT.
- "Process Tomography - the state of the art", Beck, Dyakowski and Williams, Trans Inst MC, Vol. 20, No. 4, 1998.
  Comments: Review paper on electrical tomography with specific references to ECT.
- "Calibration of capacitance tomography systems: a new method for setting system measurement range", Yang, Meas. Sci Technol 7, (1996), pp 863-867.
  Comments: Discussion of calibration methods for ECT.

- "Electrical capacitance tomography for flow imaging: system model for development of image reconstruction algorithms and design of primary sensors", Xie, Huang, Hoyle, Thorn, Lenn, Snowden and Beck, IEE Proceedings - G, Vol. 139, No. 1, February 1992.
  Comments: Title accurately describes contents of paper.
- "Experimental evaluation of capacitance tomographic flow imaging systems using physical models", Xie, Huang, Lenn, Stott and Beck, IEE Proc. - Circuits Devices Syst., Vol. 141, No. 5, October 1994.
  Comments: Experimental evaluation of ECT using test objects.
- "A mathematical model for the multi-electrode capacitance sensor", Oakley and Bair, Meas. Sci. Technol. 6 (1995) pp 1617-1630.
  Comments: Derivation of a model for the relationship between permittivity change and capacitance change inside a circular ECT sensor.

2. Image Reconstruction Methods

- "Electrical capacitance tomography for flow imaging: system model for development of image reconstruction algorithms and design of primary sensors". Xie, Huang, Hoyle, Thorn, Lenn, Snowden and Beck, IEE Proceedings-G, Vol. 139, no. 1, February 1992
  Comments: Detailed information on the image reconstruction methods used in the UMIST ECT system.
- "A review of reconstruction techniques for capacitance tomography", Isaacson, Meas Sci. Technol 7 (1996), pp 325-337.
  Comments: The title accurately describes the contents of this paper
- "Optimization of an iterative image reconstruction algorithm for electrical capacitance tomography", Liu, Fu and Yang, Meas. Sci. Technol. 10 (1999) L37-L39.
  Comments: Describes how an optimization technique for determining the gain applied to the feedback loop of an iterative algorithm can cause the algorithm to converge rapidly to produce an optimum image.
- "An improved normalization approach for electrical capacitance tomography", Yang and Byars, Proceedings of the 1st World congress on Industrial Process Tomography, Buxton, England, April 1999.
  Comments: Describes how the use of a series capacitance model can improve the accuracy of ECT images for lean phase applications.
- "An image reconstruction algorithm based on Landweber's iteration method for electrical -capacitance tomography", Yang, Spink, York and McCann, Meas. Sci. Technol. 10(1999) pp1065-1069.
  Comments: A good description of iterative image reconstruction methods.
- "Application of conjugate harmonics to electrical process tomography", Ostrowski, Luke and Williams, Meas. Sci. Technol. 7 (1996) pp 316-324.
  Comments: An analytical method for solving the electric field distribution inside an ECT sensor.

3. Applications of ECT

- "Experimental evaluation of capacitance tomographic flow imaging systems using physical models". Xie, Huang, Lenn, Stott and Beck, IEE Proceedings-Circuits Devices Syst., Vol. 141, no. 5, October 1994 1992
  Comments: Results of experiments comparing physical phantoms with ECT images.
- "Electrical capacitance tomography measurements of gravity-driven granular flows", Hua and Wang, Ind. Eng. Chem. Res., 1999, 38 pp 621-630.
  Comments: A detailed description of the use of twin-plane ECT and correlation techniques to measure the flow of particles falling under gravity in a vertical tube. The flow measurements were checked against a load cell and good agreement was obtained.
- "Combustion imaging from electrical impedance measurements", Waterfall, He, White and Beck.
  Comments: Describes how ECT can be used to image flames and combustion with experimental results.
- "Calibration of capacitance tomography systems for liquid-liquid dispersions", Bolton, Korchinsky and Waterfall, Meas. Sci. Technol. 9 (1998) pp 1797-1800.
  Comments: Describes some of the problems of calibrating ECT systems for use with water.
- "Real-time visualization and analysis of dense-phase powder conveying", Ostrowski, Luke, Bennett and Williams, Powder Technology, 102 (1999) pp 1-13.
  Comments: Describes the use of ECT to monitor powder flow in a pneumatic conveying rig.
- "Measurement of bulk particulates on a belt conveyor using dielectric tomography", Williams, Luke, Ostrowski and Bennett, Proceedings of the 1st International Symposium on on-line flow measurement of particulate solids, University of Greenwich, 14-15 July 1998.
  Comments: Describes the use of ECT to monitor particle flow on a belt conveyor.
- "Real time imaging of dense phase particulate flows in conveying and fluidization", Williams, Luke, Ostrowski and Dyakowski, Proceedings of the 1st International Symposium on on-line flow measurement of particulate solids, University of Greenwich, 14-15 July 1998.
  Comments: Contents as title.
- "Visualization of transient two-phase flows using multi-electrode capacitance sensors for electrical tomography", Reinecke and Mewes, International symposium on two-phase flow modeling and experimentation, Italy, October 1995.,
  Comments: Use of ECT to measure liquid flows in trickle-bed reactors.
- "Monitoring water hammer by capacitance tomography", Yang, Adam, Watson and Beck, Electronics Letters, 12 September 1996, vol. 32, no. 19.
  Comments: Use of ECT to monitor water hammer in long pipelines.
- "Analysis and flow regime identification of bubble column dynamics", Bennett, Luke, Jia, West, and Williams, Proceedings of the 1st World congress on Industrial Process Tomography, Buxton, England, April 1999.
  Comments: Similar to

- "Measurement of Bulk Particulates on belt conveyor using Dielectric tomography", Williams., Luke, Ostrowski and Bennett, Proceedings of the 1st World congress on Industrial Process Tomography, Buxton, England, April 1999. Comments: Similar to
- "Monitoring flame position and stability in combustion cans using ECT", Waterfall, He, Wolanski and Gut, Proceedings of the 1st World congress on Industrial Process Tomography, Buxton, England, April 1999.
- "Internal structures in fluid beds of different scales: an application of electrical capacitance tomography", White and Zakhari, Proceedings of the 1st World congress on Industrial Process Tomography, Buxton, England, April 1999. Comments: ECT imaging of fluidization of alumina particles in different diameter fluidized beds.
- "ECT studies of bead fluidization in vertical mills", Scott and Gutsche,, Proceedings of the 1st World congress on Industrial Process Tomography, Buxton, England, April 1999.
  Comments: Use of ECT to measure the media packing and fluidization in an agitated vertical mill.
- "Particle extraction using process CT and Wavelets", Takei, Li, Ochi, Saito, Horii and Dyakowski, Proceedings of the Second Japanese-European 2-phase flow group meeting, Tsukuba, Japan, September 25-29, 2000.
  Comments: Use of wavelet analysis to improve accuracy of ECT data for concentration profile measurement in a powder-conveying pipeline.
- "Imaging immiscible liquid-liquid systems by capacitance tomography", Bolton, Korchinsky and Waterfall, Trans IChemE, Vol. 77, Part A, November 1999, pp 699-708.
  Comments: Use of ECT to image water droplets in kerosene.
- "Imaging nylon polymerization processes by applying electrical tomography", Dyakowski, York, Mikos, Vlaev, Mann, Follows, Boxman and Wilson, Chemical Engineering Journal, 77, (2000) pp 105-109.
  Comments: Title accurately describes contents of paper.

4. Some Other Relevant Papers

- "Capacitance transducers for concentration measurement in multi-component flow processes", Huang, Green, Stott and Beck, Proceedings of the 3rd International Conference on Multiphase flow, The Hague, the Netherlands, May 1987.
  Comments: Describes how multiphase flow can be measured using an array of capacitance transducers.
- "Flow imaging for multi-component flow measurement", Plaskowski, Beck and Krawaczynski, Trans. Inst. M.C. Vol. 9, no. 2, April-June 1987.
  Comments: Describes how multiphase flow can be measured using concentration and velocity profiles.
- "Comparison of the use of internal and external electrodes for the measurement of the capacitance and conductance of fluids in pipes", Stott, Green and Seraji, J.

Phys. E: Sci.Instrumen., vol. 18, 1985.
Comments: See title. Useful paper for understanding the choice between capacitance sensors with internal and external electrodes.

- Textbook, "Capacitive sensors", Baxter, IEEE press, ISBN 0-7803-11.30-2.
Comments: A mine of practical information on capacitive sensor design.

APPLICABLE EQUATIONS

Gauss's law.

$$\oint \vec{E} \bullet d\vec{a} = \frac{q}{\varepsilon_0};$$

Capacitor equation.

$$C = \frac{Q}{V};$$

Capacitive impedance.

$$Z = \frac{1}{j\omega C};$$

Total capacitance for parallel circuit arrangement.

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_n}$$

Total capacitance for series circuit arrangement.

$$C = C_1 + C_2 + C_n$$
