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# CONSITENCY PROFILE MEASUREMENT IN PULP BASED ON ELECTRICAL IMPEDANCE TOMOGRAPHY

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**Abstract** − This paper describes a low cost system to measure the consistency profile of pulp based on electrical impedance tomography (EIT). A 16-electrode sensor is applied to acquire the cross-sectional data. Data acquisition is controlled by a single-chip computer, which receives commands from host computer, initializes hardware, acquires data and sends them to host computer via a serial port. All the measurement parameters such as the amplitude and frequency of the injected current can be set by software in host computer. The consistency profile image is reconstructed by modified Newton-Raphson algorithm. Comparing to conventional method, it is non-invasive and low cost.

**Keywords**: tomography, EIT, consistency profile

## 1. INTRODUCTION

In pulp and paper making, the control of the pulp slurry consistency is especially important. Without uniform consistency the process is practically impossible to control. Whether the uniformity is achieved with instrumentation or by other means, it must be measured. The manual method of measuring consistency consists of selecting and weighing a representative sample, removing the water, and weighing the reminder. This method is satisfactory for spot checking but it is not acceptable for continuous control. Changes in consistency must be monitored continuously and online if satisfactory control is to be achieved. For control purposes, it is important to be able to sense the variations in consistency rather than to determine the absolute value of consistency [1].

The conventional measuring instruments are unsuitable for this purpose, because they may not work in the difficult internal conditions of the process, or disturb the operation of the process. The measuring instruments for such applications must use robust, non-invasive sensors. Computerized Tomography (CT) has been used widely in modern medicine. Since 1990s, scientists started to develop multiphase flow measurement based on tomography in order to get a more illustrative and accurate result. The image data can be analysed quantitatively for subsequent use to actuate process control strategies or to develop models to describe individual processes [2].

Electrical impedance tomography (EIT) is an imaging method that can profile the resistivity distribution within a domain. For suspensions, such as pulp in water, it is possible to estimate the concentration of the dispersed phase from resistivity measurements. The advantage of such a technique over many other measurement methods is that it provides a non-invasive and sensitive method of measuring the pulp flow using non-ionising radiation. The relative low cost and its suitability to perform long term monitoring are also very desirable features. The EIT imaging is not affected by the opacity of suspensions. Thus, it can be used for dense or coloured suspensions. Also, the measurements can be made without perturbing the flow of the suspension.

Emmanuel O. Etuke et al. designed an EIT system to measure pulp suspensions in a shallow flow [3]. Experiments were conducted on a laboratory-scale flow rig that was constructed to simulate the spreading of pulp from a headbox. EIT measurements were acquired from a set of linear array electrodes flush-mounted to the base of the slice opening located at the bottom of the headbox. The EIT measurements were derived from a ‘sliding’ measurement protocol that involves selectively scanning subsets of the electrode array while using the standard adjacent measurement protocol. The results of the experiments show that EIT can resolve pulp consistency down to 0,1% with a spatial resolution that is less than 1 cm. This work will lead to innovative instrumentation where EIT measurements could be used in a feedback control setup for producing high quality paper in an efficient and economic manner.

## 2. MEASUREMENT SYSTEM

The basic idea of process tomography is to install a number of sensors around the pipe or vessel to be imaged. This reveals information on the nature and distribution of components within the sensing zone. The sensor output signals depend on the position of the component boundaries within their sensing zones. Most tomographic techniques are concerned with abstracting information to form a cross-sectional image. A computer is used to reconstruct a tomographic image of the cross-section being observed by the sensors. This will provide, for instance, identification of the distribution of mixing zones in stirred reactors, interface measurement in complex separation processes and measurements of two-phase flow boundaries in pipes with applications to multiphase flow measurement. The image data can also be analysed quantitatively for subsequent use to improve process control or to develop models to describe individual processes.

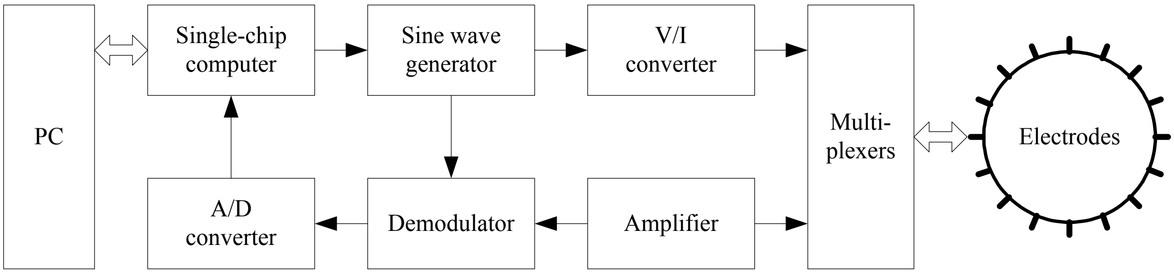

Fig. 1. Schematic diagram of the system

In our project, a 16-electrode EIT system is used to measure the resistivity distribution of pulp in a pipe, then the consistency and consistency profile can be analysed. The schematic diagram of the system is shown in Fig. 1.

Sine wave is generated by an EPROM-based function generator, see Fig. 2. A synchronous signal is also generated for demodulation purpose. The output frequency can be selected among 153 Hz, 200 Hz, 300 Hz … 19.5 kHz by different factor of frequency divider. The amplitude of the output wave is controlled by the reference voltage of DAC1. Therefore, we can change the output voltage of DAC2 to obtain the desired amplitude of the output wave.

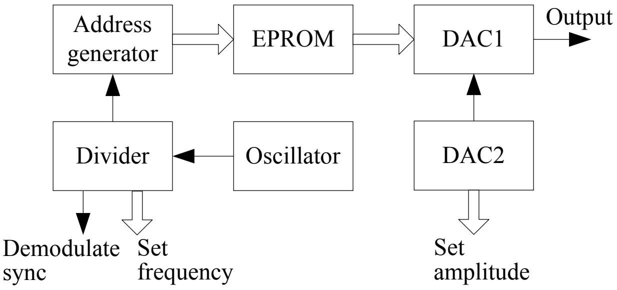

Fig. 2. Sine wave generator

The electrode signals are first amplified by programmable gain amplifier, which provides gains of 1, 10, 100 and 1000. Resistivity signal is demodulated by a phase-sensitive demodulator AD630 and digitized by a 12-bit A/D converter, see Fig. 3. The single-chip computer accepts commands from host computer to initialize the hardware (gain of amplifier, amplitude of injected current, sample interval and so on), selects electrodes for injecting current and electrodes for collecting voltage signals, controls the A/D converter to acquire data and sends the sampled data to host computer via serial port. The whole system is simple, flexible and low cost.

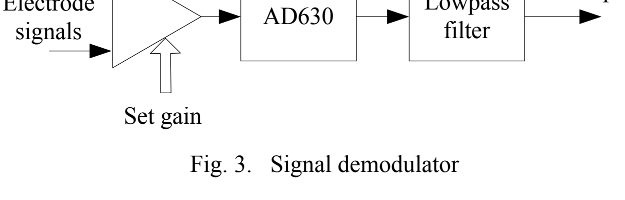

Fig. 3. Signal demodulator

## 3. IMAGE RECONSTRUCTION

In order to obtain the cross-sectional image from the data acquired by the electrodes, a reconstruction algorithm is used. Many reconstruction algorithms have been developed. Generally, a non-iterative method needs a short calculation time but the precision is low; Iterative method gives a higher precision but needs a longer calculation time. In our study, the modified Newton-Raphson algorithm is applied to reconstruct the resistivity map of the cross-section, which minimizes the mean square difference between the measured and estimated voltage response [4].

$$\Phi(\rho) = \frac{1}{2}[f(\rho) - V_0)^T][(f(\rho) - V_0)] \quad (1)$$

where $V_0$ is the measured voltage and $f(\rho)$ is the estimated voltage for a resistivity distribution $\rho$. The resistivity distribution is iterated until the convergence criterion is met, using

$$\rho^{k+1} = \rho^k + \Delta\rho^k \quad (2)$$

where

$$\Delta\rho^k = -(J^T J)^{-1} J^T [f(\rho^k) - V_0] \quad (3)$$

where $\boldsymbol{J}$ is the Jacobian matrix, the product of the transposed Jacobian and itself forms an approximation of Hessian matrix, which is often ill conditioned. This makes the inverse difficult to calculate and sensitive to measurement errors. Ill-conditioning arises from the non-linear behaviour of the resistivity distribution with respect to the measured boundary voltages (for example, resistivity changes in elements situated at the centre part produce virtually no significant changes in boundary voltages) [2]. Furthermore, the positive definiteness of the Hessian matrix deteriorates due to numerical rounding errors and the poor initial guess of $\rho$, in such instances, the algorithm often diverges and results in negative values of resistivity. Therefore, the regularized resolution is needed. A common solution is of the form

$$\Delta\rho^k = -(J^T J + \omega^k A)^{-1} J^T [f(\rho^k) - V_0)] \quad (4)$$

where $\boldsymbol{A}$ is the regularization matrix, $\omega$ is the smoothing factor. The choice of matrix $\boldsymbol{A}$ is very important. Vauhkonen

M et al. explored the problem comprehensively [5]. It should be noted that the identity matrix ***I*** and diag($J^TJ$) are often used as regularization matrix for general purpose. A large $\omega$ can improve the ill-condition, but the convergence speed will become slow. So, the value of $\omega$ should be updated according to the result of iteration. If $\Phi(\rho^{k+1}) < \Phi(\rho^k)$, $\omega$ is divided by $K$ (larger than 1), otherwise multiplied by $K$ or set to initial value. The initial value is often chosen as 0.1.

In our study, the number of electrodes is 16. In order to avoid electrode contact impedance problem, the voltages are not measured at those current-injecting electrodes. Therefore, if we use adjacent measurement strategy, the total number of independent measurements is 16×(16-3)/2=104. If the opposite measurement strategy is used, then the number of independent measurements is 8×(16-4)=96 [6].

To estimate the voltage *f(ρ)* for a resistivity distribution *ρ*, a finite element mesh of 66 nodes and 104 triangular elements is used, see Fig. 4. The black dots are the places of electrodes. The basic steps of calculating are as follows:

a) Forward problem: guess initial *ρ*, apply finite elements to estimate the potential distribution, and then calculate the boundary voltage.
b) Calculate the error sum according to formula (1), if it is less than the prescribed error limit, then stop iteration, otherwise, go to c).
c) Inverse problem: calculate $\Delta\rho$ according formula
on.

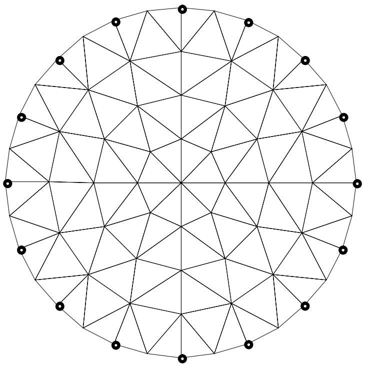

Fig. 4. Finite element mesh

## 4. EXPERIMENTAL RESULTS

The experiments were carried out in a cylindrical tank of 60 mm diameter with 16 circular stainless steel electrodes of 6 mm diameter. The tank was full of pulp (about 3,5% consistency) and some plastic rods were used to form several different areas of resistivity, see Fig. 5. The injected current was set to 2,0 mA/1kHz.

A typical data set is shown in Fig. 6 (adjacent measurement strategy, 104 measurements). The pictures in Fig. 7 show the results that a plastic rod of 20 mm diameter was placed in different positions.

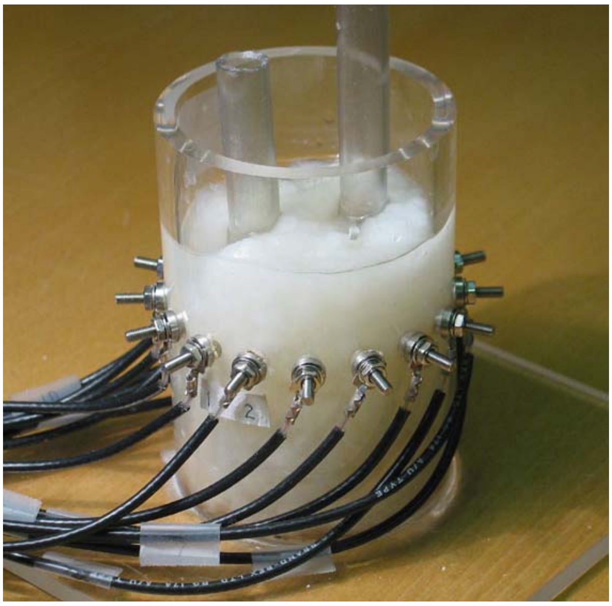

Fig. 5. 16-electrode sensor

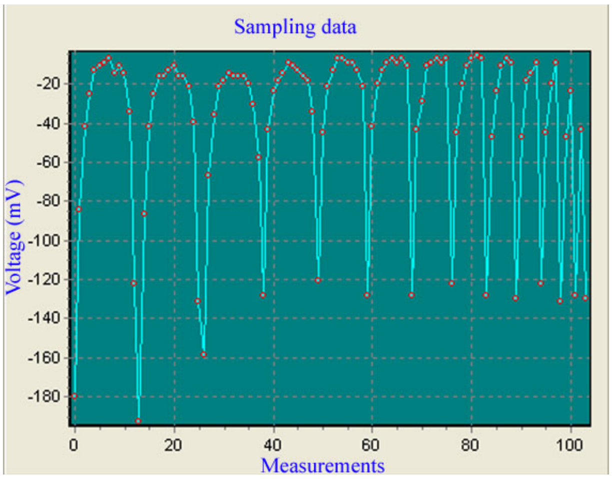

Fig. 6. A typical data set

## 5. CONCLUSIONS

A low cost prototype EIT system has been constructed to measure the consistency profile of pulp. The preliminary results show that the resistivity distribution in pulp can be measured by EIT technique. Data collection controlled by single-chip computer offers a robust solution—data sampling and image reconstruction are made simultaneously and it is easy to change the parameters and strategy of data collection by software. This system is currently targeted at monitoring the pulp flow online. So, decreasing the time of data collection and simplifying the iterative algorithm will be the task of next stage.

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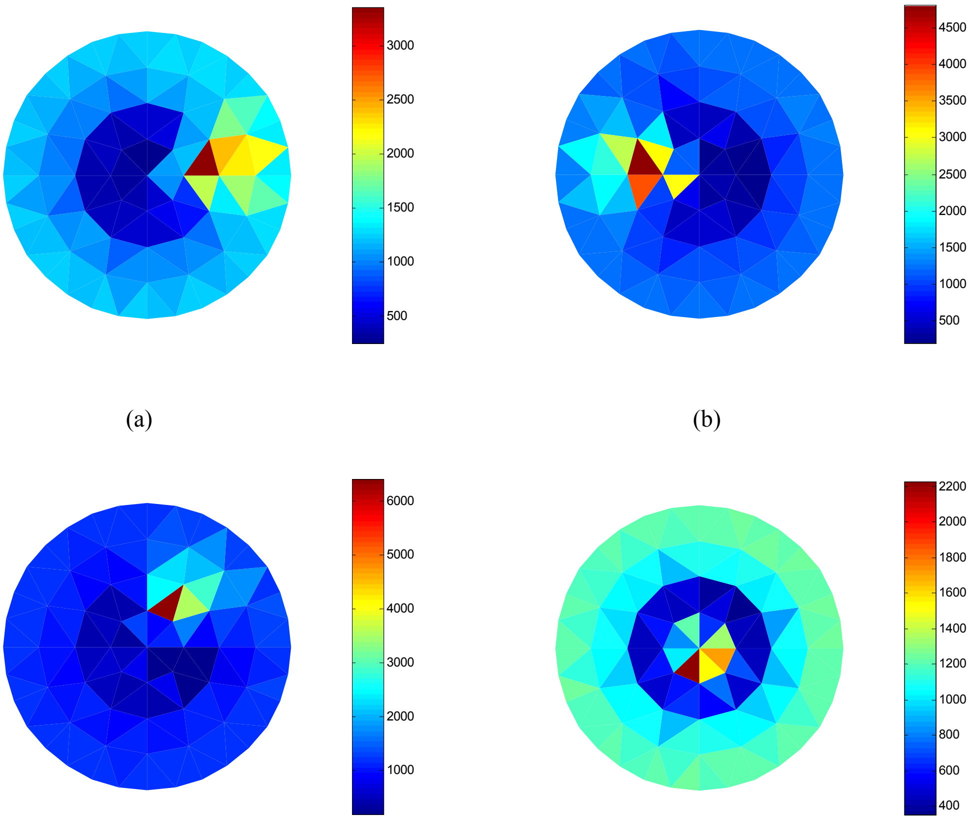

(a) (b)

(c) (d)

Fig. 7. Experimental results. a) Plastic rod on the right; b) Rod on the left; c) Rod near centre; d) Rod at the centre.

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