OPTIMIZATION OF ELECTROSTATIC SENSOR FOR VELOCITY MEASUREMENT BASED ON PARTICLE SWARM OPTIMIZATION TECHNIQUE

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Dedicated to my beloved husband,Farshid Rohani, my lovable sons, Mobin and Radin Rohani especially my respected parents, Nasrolla Heydarianasl and Hakime Rezaee and my supportive supervisor – Prof. Dr. Mohd Fua'ad B. Hj Rahmat. Thank you very much for being supportive, helpful and understanding.

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Mozhde Heydarianasl

ABSTRACT

Electrostatic sensors are broadly applied to measure velocity of solid particles in many industries because controlling the velocity particles improves product quality and process efficiency. These sensors are selected due to their robust design and being economically viable. Optimization of different electrode sizes and shapes of these sensors is required to find the ideal electrodes associated with maximum spatial sensitivity and minimum statistical error. Uniform spatial sensitivity is a crucial factor because it would lead to increase similarity between the measured correlation velocity and true mean particle velocity. This thesis proposes a new method to optimize different parameters of electrodes for electrostatic sensors. This technique identified characteristics of the electrostatic sensor in a MATLAB code called Particle Swarm Optimization (PSO). A mathematical model of various electrodes to compute spatial sensitivity and statistical error was applied to extract geometric size information of electrodes to detect suitable equations. To validate the proposed method, different values of electrode designs were applied in experimental tests conducted in a laboratory to measure the velocity of solid particles. The experimental results were optimized through Response Surface Methodology (RSM), an optimization technique for experimentation. The optimized results showed that spatial sensitivity of circular-ring electrode is more uniform in comparison to the other electrodes. The optimal length of circular-ring electrode was between 0.577 cm and 0.600 cm. In addition, the best thickness for the electrodes was between 0.475 cm and 0.500 cm. A close agreement between optimization and experimentation verifies that the proposed method is feasible to optimize physical sizes of electrostatic sensor electrodes. These results provide a significant basis of the effect of geometric dimensions on the sensing characteristics of electrostatic sensors.

ABSTRAK

Penderia elektrostatik digunakan secara meluas bagi mengukur halaju zarah pepejal dalam pelbagai industri kerana dengan mengawal halaju zarah dapat meningkatkan kualiti produk dan kecekapan proses. Penderia ini dipilih disebabkan oleh reka bentuknya yang kukuh dan lebih ekonomi. Pengoptimuman saiz dan bentuk elektrod yang berbeza daripada penderia ini diperlukan untuk mendapatkan elektrod yang sesuai berkaitan dengan kepekaan ruang yang maksimum dan ralat statistik yang minimum. Kepekaan ruang yang seragam merupakan faktor penting kerana dapat meningkatkan persamaan antara halaju sekaitan terukur dengan min sebenar halaju zarah. Tesis ini mencadangkan kaedah baharu untuk mengoptimumkan parameter elektrod yang berbeza bagi penderia elektrostatik. Teknik ini mengenal pasti ciri-ciri penderia elektrostatik pada kod MATLAB yang disebut sebagai Pengoptimuman Kumpulan Zarah (PSO). Model matematik pelbagai elektrod bagi mengira kepekaan ruang dan ralat statistik digunakan untuk mendapatkan maklumat saiz elektrod geometri untuk mengesan persamaan yang sesuai. Bagi mengesahkan kaedah yang dicadangkan, nilai-nilai berbeza reka bentuk elektrod digunakan dalam ujian eksperimen yang dijalankan di makmal untuk mengukur halaju zarah pepejal. Kerumunan eksperimen dioptimumkan melalui Metodologi Permukaan Gerak Balas (RSM), iaitu sebuah teknik pengoptimuman bagi ujikaji. Keputusan optimum tersebut menunjukkan bahawa kepekaan ruang elektrod gelang bulat lebih seragam berbanding dengan elektrod-elektrod lain. Panjang optimum elektrod gelang bulat adalah antara 0.577 cm dengan 0.600 cm. Di samping itu, ketebalan paling sesuai elektrod adalah antara 0.475 cm dengan 0.500 cm. Perjanjian rapat antara pengoptimuman dan eksperimen mengesahkan bahawa kaedah yang dicadangkan boleh dilaksanakan untuk mengoptimumkan saiz fizikal elektrod penderia elektrostatik. Keputusan ini menyediakan asas yang besar daripada kesan dimensi geometri kepada ciri-ciri penderiaan penderia elektrostatik.

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LIST OF ABBREVIATIONS

2D	-	Two Dimensions
3D	-	Three Dimensions
AC	-	Alternating Current
DC	-	Direct Current
DAQ	-	Data Acquisition
FEM	-	Finite Element Modeling
FFT	-	Fast Fourier Transform
HHT	-	Hilbert-Huang Transform
PC	-	Personal computer
SEE	-	Standard Error of Estimation
S	-	Spatial Sensitivity
GA	-	Genetic Algorithm
PSO	-	Particle Swarm Optimization
MOPSO	-	Multi objective Particle Swarm Optimization
A/D	-	Analogue to digital
ESA	-	Electrostatic Sensor Arrays
E	-	Electrical field
q	-	Point charge
Q	-	Induced charge
L	-	Length of electrode
W	-	Width of electrode
T	-	Thickness of electrode
d	-	Diameter of electrode
D	-	Distance between electrodes

LIST OF SYMBOLS

t	-	time
m	-	meter
f	-	Frequency
Hz	-	Hertz
λ	-	Mean Free Pass, Wave Length
x	-	x axis, Wave Distance to Transmitter
α	-	Attenuation Coefficient, Constant
R_f	-	Feedback Resistance, Equivalent Resistance
C_f	-	Feedback Capacitor, Equivalent Capacitor
θ	-	A Selected Angle
σ	-	Charge Density, Statistical error
ρ_v	-	Volume Charge Density
Γ_s	-	Boundary Conditions for Metal Screen
Γ_e	-	Boundary Conditions for Electrode
Γ_p	-	Boundary Conditions for Pipe
r	-	Distance from Center of the Particle, Distance from Center of the Ring electrode, Particle Radial Position
ε_0	-	Electric Permittivity for Free Space
g	-	Gravity Acceleration, Constant
V	-	Voltage
v	-	Velocity
V_C	-	Correlation Velocity
V_m	-	Mean Particle Velocity
$S(x)$	-	Electrode Sensitivity in x axis
$S(z)$	-	Electrode Sensitivity in z axis
$S(r)$	-	Electrode Sensitivity in r axis
$h_S(t)$	-	Impulse Response

$H_S(f)$	-	Frequency response
W_e	-	Spatial Filtering Length
$\sigma(\tau_m)$	-	Statistical error of transit time
τ_m	-	Transit time

CHAPTER 1

INTRODUCTION

1.1 Introduction

Electrostatic sensors are normally robust and inexpensive since they do not require an external source. This sensing approach has attracted significant attention from the flow measurement community. In this approach, movement of particles in a pneumatic conveyor will generate an electrostatic charge on the particles because of their interaction with each other, the pipeline and conveying air. The amount of charge depends on the physical and chemical properties of the particles and surrounding environment in the pipeline (Shao *et al.*, 2010; Shao *et al.*, 2009; Tajdari and Rahmat, 2014; Taylor, 2001).

A major advantage of using an electrostatic sensor is its high sensitivity for concentration metering. If an electrostatic sensor is combined with cross correlation method to measure the velocity, the most economical and inexpensive method to measure moving particles velocity in pipelines would be provided due to the fact that electrostatic sensor only responds to moving solids in a pipeline and the measured data have a large number of immunity from the effect of solids accretion which adversely affects other technologies (Zhang and Yan, 2003).

There are two methods to install electrostatic sensor to a pipeline which are non- intrusive arrangement and intrusive arrangement (Mustafa, 2011). In addition, electrostatic sensors consist of different types of electrodes including circular- ring, quarter- ring, pin and rectangular. The circular or ring sensor are normally embedded in the pipe via insulator which is a non-intrusive arrangement. The reason this type of sensor is widely studied in research is that circular electrodes are able to average the flow of particles and have relatively uniform sensitivity (Shao *et al.*, 2009). However, in the pipeline industry, this arrangement can be expensive since the diameter of a pipe for use in power plants is large. On the other hand, the rode electrode or pin sensor which is an intrusive arrangement can easily be mounted around the pipeline at various locations. Based on Shao *et al.* (2009) research, a rod sensor has stronger signal and higher correlation coefficient than circular sensor. It is also sensitive to localized information of flow based where the electrode is located. In addition, a circular electrode can detect complex signal produced by particles in the pipe line. The researchers also stated that circular and rod electrodes have excellent dynamic response, and are essential for rapid change in velocity of particles.

There are many methods used to measure particles velocity such as particle images velocimetry (PIV), Doppler methods, spatial filtering and cross correlation method. Cross correlation technique is extensively used in laboratory and pipelines industry for velocity measurement. In addition, this method is applied two sensors to measure the velocity. The sensor used in this project was electrostatic sensor. The selection is based on the particle charging of solid flows (Rahmat and Kamaruddin, 2009). Moreover, this sensor has the advantages of having a simple structure, non-contact or non- invasive measurement, highly sensitive, low cost and is a safe sensor for the harsh industrial environment. The sensing technique used in velocity measurement consists of four basic subsystems that include sensing, signal conditioning, data acquisition and display system. The sensor or sensing system is used to detect particles flow and located at the upstream and downstream positions while signal conditioning circuit is used to convert electrical charge from an electrode to a voltage signal of certain amplitude. Data acquisition system, DEWE-T-DSA-141 is applied to save and analyze the output signals of electrostatic sensors. For the display system, a PC is used to monitor voltage signals produced through DAQ. This basic system of the measurement system is shown in Figure 1.1.

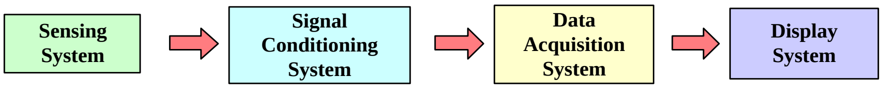

Figure 1.1 Measurement system

This research coped with optimization of electrodes of electrostatic sensors by measuring solids velocity. To achieve this target, a mathematical model of several electrodes was examined and uniform spatial sensitivity was surveyed. A novel method was proposed to optimize probes size and to consider in detail how to obtain the probes volume information for electrostatic sensor.

1.2 Optimization of Electrostatic Sensor

Electrostatic sensors have recently been used in many industries and laboratories since they are vigorous, simple, and easy to install. Although there are numerous applications of these sensors, they have problems with optimization. Electrostatic sensors need to be optimized to achieve the desired optimal electrodes. Furthermore, optimization of electrostatic sensor is important to maximize spatial sensitivity and minimize statistical error.

Some researchers have optimized electrostatic sensors by using various methods such as finite element modeling (FEM) (Tajdari *et al.*, 2012), Genetic Algorithm (GA), and ANSYS. However, this optimization needs further research to achieve the best volume for the different parameters of electrostatic sensor. GA is an evolutionary computation technique. PSO shares many similarities with GA. The system is initialized with a population for random solutions and searches for optima by updating generations. However, unlike GA, PSO does not have evolution operators such as crossover and mutation (Eberhart and Shi, 1998). In PSO, the potential solutions, called particles, fly through the problem space by following the current optimum particles. Compared to GA, the PSO technique is more dependable used to optimize electrostatic sensors as it does not consist of evolution operators. Moreover, the PSO approach has fewer parameters to adjust besides being easy to implement. Therefore, PSO due to its advantages is more feasible for use in the optimization of electrostatic sensors.

PSO is a simple, effective, and computational technique that optimizes a problem by iteratively trying to improve a candidate solution with regard to a given measure of quality. This technique can be used for multi- parameter optimization which also uses population- based approach. At first, PSO was put forward by Kennedy and Russel based on bird's flocking and fish schooling (Kennedy and Eberhart, 1997). Generally, the PSO approach has been used in many applications. Multi- objective particle swarm optimization (MOPSO) is a type of PSO method applied for multi- objective functions. It is more feasible to be used in this study since spatial sensitivity and statistical error of electrostatic sensors should be simultaneously optimized.

1.3 Velocity Measurement

Velocity measurement has the most significant role in managing and monitoring particles manner (Li *et al.*, 2006; Yutao *et al.*, 2011). Electrostatic sensors are used due to their proficiency in providing dependable velocity in pneumatic conveying solid particles with exceptional repeatability and reckless dynamic reaction under industrial situation.

There are two types of velocity, namely linear and rotational (angular) (Zhang *et al.*, 2010a). Linear and rotational velocities relate the speed of an object or particle, dependent on the perspective taken. Linear velocity utilizes to any object or particle that moves, while rotational velocity applies to those that turn such as a wheel or a spinning top. Velocity is a physical vector quantity; both magnitude and direction are needed to define it. The speed is the scalar absolute value (magnitude) of velocity. Linear velocity is generally realized as velocity.

The following method is used to measure linear velocity. Differentiation of displacement or integration of acceleration frequently gets the velocity. The essential equations to measure the mean velocity is as follows:

$$v_{avg} = \frac{y_2 - y_1}{t_2 - t_1} = \frac{\Delta y}{\Delta t} \tag{1.1}$$

where v_{avg} denotes mean particle velocity, t_1 to t_2 is time interval and y denotes position.

The method for velocity measurement is divided into two categories which are referenced- based methods and seismic or inertial referenced transducers. In addition, there are two variations for referenced-based measurement. Firstly, the average speed for classification of positions can be determined by means of a series of similarly spaced pickups. Secondly, some kind of position transducer is used to record the position. However, velocity measurement has a direct effect on uniformity of spatial sensitivity and this requires further examination.

1.4 Research Background

In this study, the measurement of velocity using intrusive electrostatic sensors was used to examine particle flow in pneumatic conveying pipeline. The electrodes in these sensor have different cross-sectional characteristics, including circular-ring, quarter ring, and rectangular. Sensor signals resulting from the applications of different shaped electrodes were compared. Cross correlation method, which measures similarity between signals, was applied for velocity measurement include. Besides that, electrode size and sensor design do affect sensor signals and measurements. Therefore both methods were applied during the investigation of pipeline velocity.

As mentioned earlier, electrostatic sensors are used in various industries because they offer measurement solutions that are efficient and cost-effective. The most frequently investigated electrode type is the non-intrusive directing ring, a circular reed sensor that follows the contours of a pipeline wall, but is separated from the wall by a non-conductive barrier. The ring electrodes are subject to various problems, as a coil is fitted into a pipeline in place of a similar sized piece of the pipe. Besides that, implementing ring electrodes is a difficult and expensive procedure, especially in long pipelines or when there are access problems. On the other hand, the pin electrode is significantly easier to mount through a hole drilled into a pipe at a prerequisite site. But they are easily damaged by strong particle flow and need to be protected to increase their robustness. Both ring and pin electrodes are most sensitive in the area immediately adjacent to the electrode.

Although there has been extensive research published on ring electrodes, there is a sparse offering of research available on intrusive electrodes. In these electrodes, the cross sectional measurement of particle flow can have several electrodes placed at the circumference of a pipeline. Their presence causes some disruption to the pipeline flow patterns. However, as they register the flow over a cross sectional area, the overall disruptive impact on the flow is not significant. The dimensions of an intrusive electrode for measuring particle velocity can be random. On the contrary, the optimum electrode design in terms of shape, size, and sensor design related to a specific pipeline dimension has yet to be determined.

1.5 Problem Statement

Use of electrostatic sensors in velocity and mass flow rate measurement has been the subject of extensive academic research (Carter *et al.*, 2009; Ibrahim and Green, 2002; Krabicka and Yan, 2007, 2009a; Rahmat and Yaw, 2012; Shao *et al.*, 2010; Shao *et al.*, 2009; Zhang *et al.*, 2012). The velocity measurement concerns the need to detect erosion or assess the maximum effective flow of solid particles and their mass flow rate in a number of industries (Gajewski, 2008; Green *et al.*, 1997; Matsusaka and Masuda, 2006; Zheng and Liu, 2011). Knowing these criteria can lead to improvement in product quality and process efficiency. When searching for the most suitable type of sensor, choosing electrostatic sensors has benefits because it has a positive impact as they are robust, inexpensive, and produce a high level of accuracy. This research examined the most suitable intrusive electrostatic sensor and the best format to obtain accurate particle flow measurements.

The problem statement of this study is expressed as follows:

“An optimized electrostatic sensor is required to achieve maximum spatial sensitivity and minimum statistical error.”

The reason why the optimization for electrode designs is need is that a uniform spatial sensitivity of an electrostatic sensor is essential in order to achieve a reliable and accurate measurement of the solids concentration area and to ensure that the instrument is able to cope with different flow regimes. Additionally, non-uniform spatial sensitivity of electrostatic sensor leads to a discrepancy between correlation velocity and mean particle velocity. This meter factor could be quantified by using optimization of electrostatic size. Optimal sensing characteristics are required to increase the performance of electrostatic sensors. The dimensions and designs of electrodes are two major parameters to obtaining better sensing characteristics of these sensors. To study the potential for improving performance of electrostatic sensors, this research used PSO method. Previous works on optimization of electrostatic sensors applied FEM and GA methods. Optimization design in that ways were complex and the finally results changed every time. So the optimal results could not be determined. The results of those methods need to be improved; hence, PSO is proposed as a new method for optimizing different types of electrodes in electrostatic sensors in current research work.

1.6 Research Objectives

The purpose of this project is to study how electrostatic sensors used to measure velocity in the pipeline can be optimized. This was done by investigating the effect of different dimensions of electrodes. To carry out this study, the research objectives are as follows:

I. To investigate the performance of different types of electrodes such as circular-ring, quarter-ring and rectangular in electrostatic sensors, and examine their capability to measure the velocity of particle flow in a vertical pneumatic pipeline.

II. To derive the mathematical model of different types of electrodes.

III. To optimize an electrode sensor design for velocity measurement using PSO technique.

In this research, a cross correlation method was used to measure the velocity of particles. A new approach was applied to optimize several electrodes of electrostatic sensor. This method called PSO gives the best size of electrodes to achieve uniform spatial sensitivity. Some electrodes of electrostatic sensor are mathematically modeled. To solve graph mathematical equations, Mathcad software was employed. MATLAB code was utilized for PSO and MOPSO techniques and optimizing electrodes. PSO is a computational method of solving a problem by optimizing it to arrive at an ideal candidate solution. The motion of a complete set of candidate solutions known as particles within a search space is based on a simple mathematical formula with reference to its position and velocity. Moreover, the PSO approach has fewer parameters to adjust and it could be easily implemented. Therefore, due to its advantages, PSO is more feasible for use in the optimization of electrostatic sensors. DEWETRON data transfer card and DEWESOFT software were employed for data collecting purpose in experimental tests. Finally, the experimental results were optimized through response surface methodology (RSM) method.

1.7 Research Scopes and Limitations

The scope of this research included a range of different kinds of electrostatic sensor electrodes for examining the efficiency in velocity measurement, and their potential to improve product quality processes. Hence, different shape of electrodes;

circular- ring, quarter- ring, and rectangular, with different geometric size were considered to measure the velocity in different separations including 5 cm, 10 cm, 15 cm, and 20 cm. Laboratory methods were applied and software was used to compare practical and theoretical results. MATLAB software was used to evaluate velocity profile. In addition, to measure velocity, cross correlation method was used to examine the relationship between two signals by taking into account transfer time and distance between upstream and downstream sensors. This method served as an entry point to interface with computational modeling using a data acquisition system to gather data from two sensors to compute the time interval of particles transitioning between the upstream and downstream sensors. Moreover, different types of electrodes were also modeled by mathematical equations from which output signals were analyzed and plotted using Mathcad software.

Physical characteristics of particles including size, conductivity, shape, and humidity have some influence on the magnitude of the charge. In addition, solid velocity and concentration are the two main parameters contributing to magnitude of the charge. All of these parameters were ignored in this study since cross correlation method is not relevant to the signal magnitude.

Basic subsystem to measure the velocity in experiment includes sensing system, signal conditioning system, data acquisition system, and display system. Signal conditioning system did not have any effect on optimized design of electrostatic sensor because optimization was done on geometry of electrodes and signal conditioning circuits only converted the output signals from electrode to voltage signal.

The major purpose of this research is the optimization of electrodes of electrostatic sensors. PSO is a simple but powerful optimization technique applied to achieve this target. Different parameters of electrostatic sensor influenced its optimization such as geometry of electrode and electrode sensing. Since PSO acts as a multi-parameter optimization method, geometry of electrodes including length and thickness were defined as PSO’s parameters in MATLAB code. After that, electrode sensing including spatial sensitivity and statistical error was maximized or minimized by PSO MATLAB code.

The limitations of the proposed and designed measurement system are listed as follows:

(i) The electrostatic probe is a major part of measurement system that detects the electric charge of particles. Therefore, the measurement system is limited to measuring the velocity of particles without any electric charge on their body. It means that, the velocity of wooden or wet particles cannot be measured by electrostatic sensor electrodes. Hence, the minimum measurable electric charge is required on body of particle.

(ii) Separation between electrodes limits the measurement accuracy. When electrodes are located very close to each other, electric field erosion takes place and correlation coefficient is decreased whereas the statistical error is increased. The inverse phenomenon is happened in far from separation. Since high correlation coefficient and low electric field are desired, separation between electrodes should be arranged correctly.

(iii) The probe of electrostatic sensor is a pin electrode. The diameter and length of pin electrode have important effects on uniformity of spatial sensitivity as they reduce the statistical error. However, these parameters of a pin electrode cannot be changed in experimental tests.

With the exception to (i), the other limitations can be improved by developing a test rig and hardware set up.

1.8 Research Contributions

The major investigation contributions for this study are as follows:

1- Various shapes of electrostatic electrodes were designed and mathematical equations of the induced charge, spatial sensitivity, as well as statistical error of the sensor were calculated.

2- The relation between spatial sensitivity and physical size of electrodes from the analytical process of electrostatic probe were found.
3- Several parameters of electrostatic probes using PSO technique were optimized.

In this research, several forms of electrostatic sensor were mathematically modeled. In addition, they were optimized using PSO method. The spatial sensitivity of different electrodes was recorded mathematically using Mathcad software, and theoretically using MATLAB software. Uniform spatial sensitivity is significant to achieve optimal size of electrodes. The obtained optimal value of electrodes was used to measure solids velocity using gravitational test rig in laboratory to verify the proposed optimization method. Besides that, experimental and modeling results were compared with each other.

1.9 Thesis Outline

A brief introduction of the whole research is provided in chapter 1. The reasons and incentives with reference to why the research was done are discussed. A brief background of electrostatic sensor, velocity measurement, and optimization of electrode are presented. The problem statement highlighted the current problem in the optimization of electrostatic sensors. The research objective and project contribution in relation to previous studies are provided.

Chapter 2 illustrates a literature review, which includes three major parts. Electrostatic sensors in various shapes are described in the first part. Additionally, signal processing system is represented. The second part examined several approaches to measure velocity. In the third part, optimization of electrostatic sensor and a new proposed method for optimization in this study are presented.

Chapter 3 provides explanation about the mathematical model of different electrodes in detail and spatial sensitivity which was plotted for each electrode. Moreover, a new signal processing circuit is proposed to improve the output signal of

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