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Sensor Design for Development of Tribo-Electric Tomography System with Increased Number of Sensors

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Abstract : Electrodynamic sensor, which can also be called as tribo-electric sensor, senses the electrostatic charge carried by the particle. The tomography system using electrodynamic sensor is called as tribo-electric tomography system. Source of the signal induced on the electrodynamic sensor is brought by the object to be measured and no excitation circuit is necessary. This electrodynamic sensing is a passive sensing and the fast and light weighted tomography system is expected. On the other hand, most of tomography system, like capacitance tomography or resistance tomography, demands excitation circuit and is an active sensing. The number of measurements with the passive sensing is equal to the number of sensors and that of active sensing is the number of the combinations of two sensors. The passive sensing tomography system demands more sensors to be settled. We plan to improve in reconstructed images by increasing the number of the electrodynamic sensors in tribo-electric tomography system. We investigate the influence of surface area to signal intensity solving the electrical field in the sensing zone using finite element method.

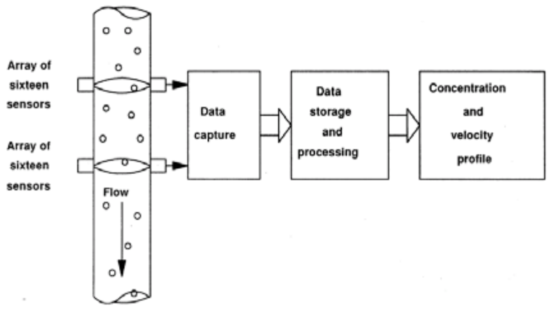
Keywords : Electrodynamic Sensor, Process Tomography, Finite Element Method, Electric Field.

1. Introduction

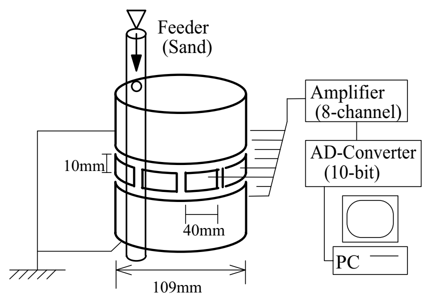
There are various tomographic methods, electrical tomography, radiation tomography, nuclear tomography, acoustic tomography and tribo-electric tomography (Beck, 1997). Process tomography mainly consists of two parts, sensing technique of plural sensors surrounding the object and image reconstruction using data from them. Process tomography does not confine the kind of sensing and any kind of sensing is available to process tomography.

The name of tribo-electric tomography comes from the way the object is electrically charged, normally contact to another materials. The name does not come from the sensing mechanism. A tribo-electric tomography bases on electrodynamic sensor and can be also called as an electrodynamic tomography. This electrodynamic sensing is well known phenomena and it detects the electrical charges carried by the object in the sensing zone. However, this sensor is called various names as tribo-electric sensor, electrodynamic sensor, displacement current sensor or influence-charge based sensor.

In 90s there are two trials to apply electrodynamic sensors to accomplish a tribo-electric tomography system. Green in Sheffield Hallan University devised a tomography system using electrodynamic sensors. His system prepares two arrays of electrodynamic sensors. One array consists of 16 sensors settled surrounding cross section of the pipe where electrically charged particles flow. Two arrays are settled along the direction of the flow and the signals from two arrays of the sensors are cross correlated to extract velocity information of the flow (Fig. 1(a)) (Bindin et al., 1995). Almost at the same time in TU-Delft Netherlands, Scarlett and Machida also built up a tribo-electric tomography system. We used one array of the electrodynamic sensors and applied Fourier transform to the signals from the electrodynamic sensors in order to extract intensity information and velocity information separately only from one stage of sensors (Fig. 1(b)) (Machida and Scarlett, 1999). Recently Fuchs in Graz University of technology developed a tribo-electric tomography system using influence-charge based sensors. This system applied two layers of the sensor and cross correlation. (Fig. 1(c)) (Fuchs et al., 2005). For the convenience, the sensor detects electrical charges is called as an electrodynamic sensor and the tomography system using electrodynamic sensor as a tribo-electric tomography system in this paper.



(a) Sheffield Univ. type



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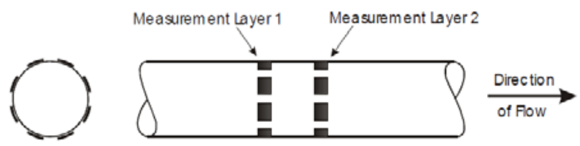


(c) Graz Univ. type

Fig. 1. Various Tribo-Electric Tomography Systems.

We are now improving a tribo-electric tomography system with one stage of the electrodynamic sensors by increasing the number of the sensors from 8 to 32. Electrodynamic sensor is a passive sensor and the number of the measurements in tribo-electric tomography system is limited to the number of the sensors, not the number of the combinations of the sensors like other active sensing. It is explained with a tomography system of 16 sensors as an example. A passive 16 sensors system can take 16 measurements through one scanning and an active 16 sensors system can take 120 measurements. Almost 8 times spatial resolution can be expected for an active sensing tomography. In other words, 8 times more sensors are demanded for a passive sensing tomography. This is a disadvantage for a passive sensing tomography system, however, a passive sensing does not demand source injection and expected to be faster than an active sensing tomography in measurement.

In our previous works, we examined the improvement by increase of the number of electrodynamic sensors. Both of back-projection and least-square method for the image reconstruction were compared using the ideal simulated data, which contained no noise. Increase of the number of the sensors brings decrease of the sensor's circumferential length and its surface area. Smaller surface area of an electrodynamic sensor induces smaller electrical current signal and relatively signal-noise ratio decreases. This paper deals with this problem, concerning the number of the sensors, the surface area of them and keeping signal intensity from them.

2. Theoretical Background for Electrodynamic Sensor

2.1 Sensing Mechanism for Electrodynamic Sensor

The Most popular electrical charge measurement method is a Faraday cage (Fig. 2(a)). Electrical flux: $\boldsymbol{E}$ radiated from electrically charged particles is captured by a Faraday cage to induce the electrical charges on the surface of the cage: $\boldsymbol{Q}_{\text{sensor}}$. The amount of the electrically induced charges is equal to the amount of the electrical charges carried by the particle: $\boldsymbol{Q}_{\text{particle}}$ when all of the electrical flux is captured. Faraday cage is connected to the capacitor whose capacitance is previously examined and known. The voltage generated the capacitor is measured to quantify the electrical charges carried by the particle. In Fig. 4, ε_0 represents permittivity of the space and $\boldsymbol{a}$ represents surface area of sensor.

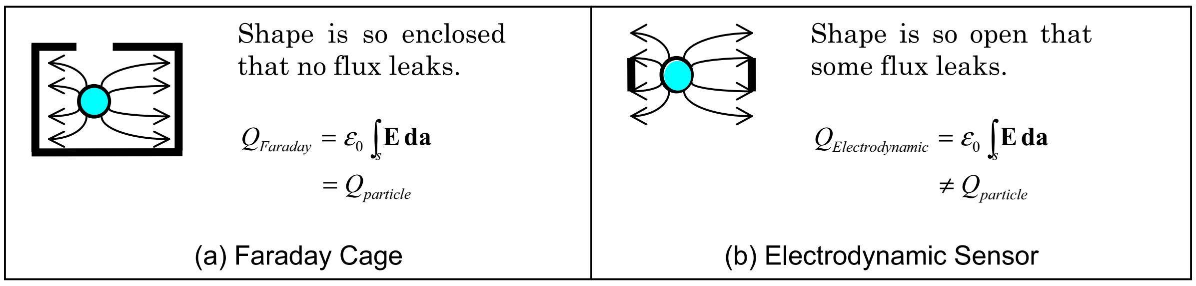


Fig. 2. Faraday Cage and Electrodynamic Sensor.

A Faraday cage normally is a cup to surround the object by the cage in order to capture all electrical flux from it. A cup disturbs the flow and becomes a destructive measurement for the flow. Our interest is not only electrical charge distribution in the sensing zone but also the movement of the object, like velocity. Therefore, we cannot adopt a Faraday cage as the sensor for the electrical charge sensing tomography system. In order to avoid the disturbance caused by the sensor, the sensor must be a plate shape and settled along a pipe surface, like an electrical resistance tomography or an electrical capacitance tomography.

This restriction for the shape is a trade off. When we change a sensor's shape from a cup to a plate, the surface area of the sensor decreases and is not large enough to capture all flux from the particle. Therefore, the amount of the induced charges on the sensor is not equal to the total amount of electric charges carried by the object, the voltage appears on the sensor cannot directly be correlated to the object's electrical charges. In this sense, this sensor is no more a Faraday cage and normally is called as an electrodynamic sensor (Fig. 2(b)).

Amount of the induced charges on an electrodynamic sensor is the sum of electrical flux captured by the sensor (Eq. 1).

$$Q_{Sensor} = \varepsilon_0 \int_s \mathbf{Eda} \tag{1}$$

This equation shows that the electrical charges induced on the sensor are the surface integral of the electrical flux reaches to the sensor. Therefore, a signal intensity from an electrodynamic sensor decreases as the sensor's surface area decreases and the signal intensity increases as the surface area increases. When we want to increase the number of the sensor aiming to improve cross sectional resolution in sensing zone, the signal from the electrodynamic sensor becomes smaller and we must consider signal-noise ratio of the signal.

2.2 Validation of Induction Model for Tribo-Electric Sensor with Experiments

In order to design the tribo-electric tomography system of 32 electrodynamic sensors, the electrical field in the sensing zone is solved using a finite element method to estimate the influence caused by decreasing size of an electrodynamic sensor. Before the design, the results obtained by field solutions using finite element method (FEM) must be validated with the experiments. Figure 3 shows the experimental rigs. The outlet nozzle of water droplets was connected to a voltage supply to give electrical charges to water droplets. In order to increase electrical conductivity, 1 % of NaCl in weight was added to water. Electrically charged droplets fell vertically and introduced to the sensing zone. The sensing zone was covered with a cylindrical metal pipe on which three electrodynamic sensors (a, b, c in Fig. 3) were mounted in vertical direction. These sensors were connected to a computer via an amplifier and AD converter was settled in the computer to capture and record the signal from the sensors. Detail of the sensor is also shown in Fig. 3. Signal from the middle sensor (sensor b) was used to compare the simulations and the ones from above and below (sensor a, c) were used to calculate the velocity of the droplets. A Faraday cage of cup shape was settled below the pipe and the charged droplets are collected. This Faraday cage was also connected to the AD converter and the amount of each electrical charge carried by the droplet was measured and recorded to the computer. After the electrical measurement, the weight of the water in the Faraday cage was measured to determine the size of the droplets.

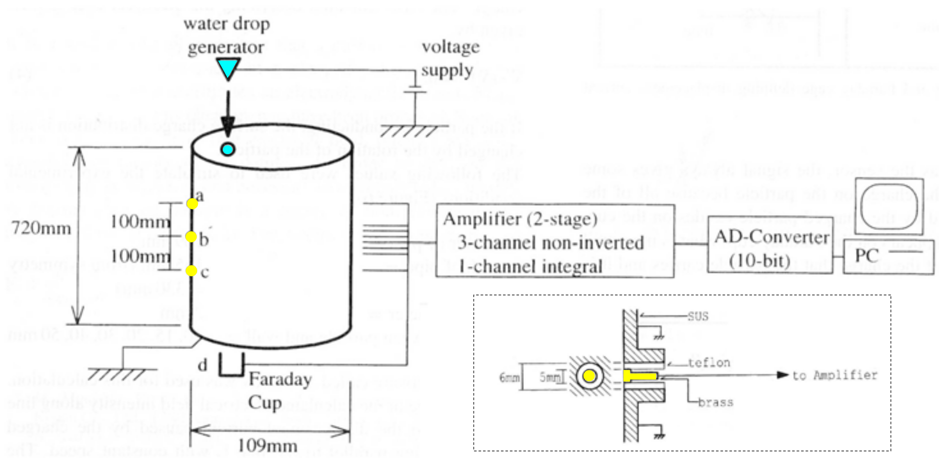


Fig. 3. Experimental Rig and Sensor's Detail.

Equation shows the governing equation for electrical field (Eq. 2). Constant permittivity distribution and electrical charges on the particle surface are assumed in the sensing zone and the governing equation becomes a Poisson's equation where V represents electric potential.

$$\nabla^2 V = Q / \varepsilon_0 \tag{2}$$

Figure 4 shows the boundary conditions used for electrical field solution using FEM. Calculation space was limited to a quarter according to its symmetries for vertical and horizontal directions. The electrical potential of the cylindrical surface connected to the earth was set to zero. Salt water was conductive and its surface was equi-potential. Therefore boundary condition of the particle was neither electrical charge distribution inside nor on the surface of the particle but the constant electrical potential on the surface. Electrical charges could freely move on the surface to make the surface potential constant and the distribution of electrical charges on the surface of particle could not be defined as boundary conditions. The distribution of electrical charges was determined with the electrical field solution. These boundary conditions are for a conductive particle. The right side of Eq. 2 becomes zero and the equation becomes Laplace equation.

Boundary conditions for nonconductive material are different because electric charges are bounded to the material and can not move freely like in the conductive. Electrical charge distribution inside or on the surface of the particle must be defined as boundary conditions and electric potential of the particle is the results of solution. Poisson equation is applied to nonconductive materials.

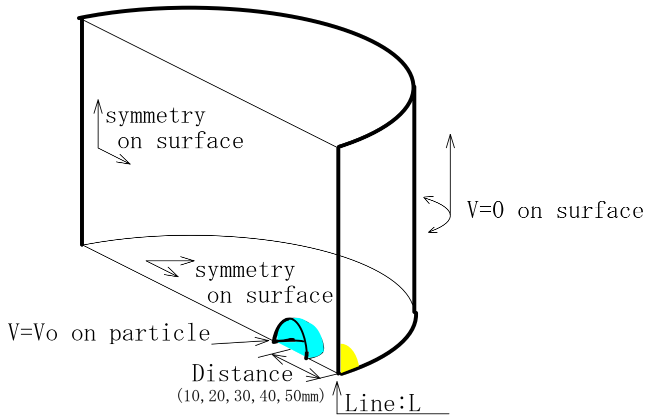
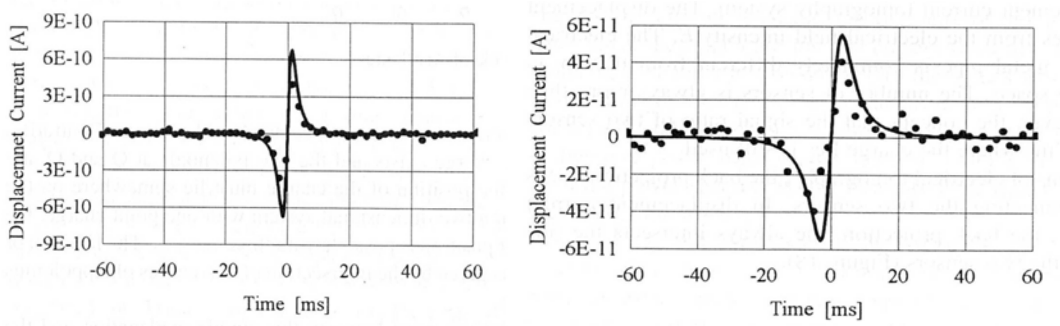


Fig. 4. Boundary Conditions for FEM.

The software Flex-PDE was used to solve the electrical field using finite element method. Results from the experiments and the field solutions are compared in Fig. 5. Dots show experimental data and lines are those from calculations. Simulation can predict the signal from the tribo-electric sensor.

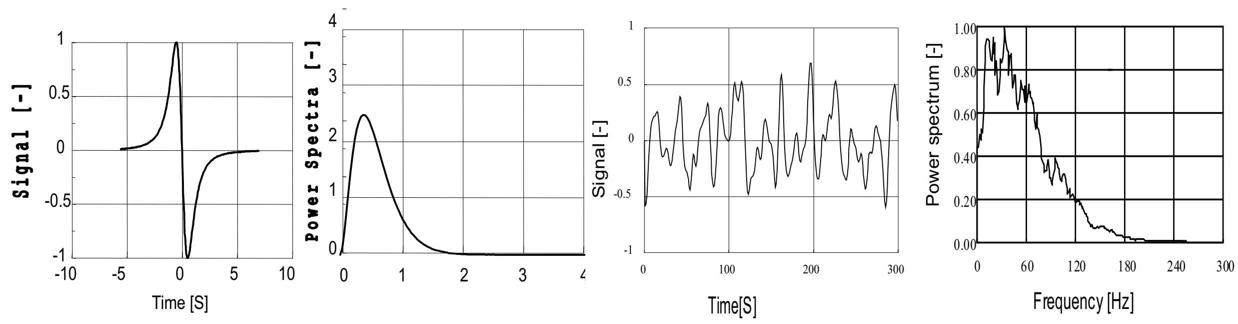


(a) Distance between Particle and Sensor = 10 mm (b) Distance = 20 mm

Fig. 5. Simulation Results and Experimental Results of Electrodynamic Sensor.

2.3 Extension to Plural Particles System Using Fourier Transform

Plural particles pass thorough sensing zone in measurement of solid flow in chemical plants. The number of particles or clouds of particles is the range from thousands to millions or billions. It is not a realistic procedure to calculate the signals induced by thousands of particles using FEM. In order to extend simulation, Fourier transform was applied to extract signal intensity from electrodynamic sensor's signal. A pulse of electrodynamic sensor's signal (Fig. 6(a)) is Fourier transformed and broad spectra are obtained (Fig. 6(b)). Many of electrodynamic sensor's signals of the same particle velocity with different amount of electrical charges were simulated using the results of electrical field solution using FEM. These signals were randomly superimposed in time domain to generate imaginary simulated data (Fig. 6(c)). These data were Fourier transformed (Fig. 6(d)) in order to confirm the shape of spectra is retained regardless the number of particles when particles pass thorough the sensing zone randomly. Though spectra were not so smooth as these by a pulse, the shape of spectra preserved in case of the signal due to many particles.



(a) A Pulse of Signal (b) Spectra of (a) (c) Superimposed Signal (d) Spectra of (c)

Fig. 6. Electrodynamic Sensor's Signal and Its Fourier Spectrum in Simulation.

After this simulations examination, experimental rig (Fig. 7) using an electrodynamic sensor of ring shape was prepared to made confirmation that the spectra of a pulse of electrodynamic sensor's signal was retained in the flow where many particles exist. Air was introduced to the bottom of a resin pipe of inner diameter of 14 mm and the air flows up vertically. The particle, in this case alumina particle (average diameter = 80 μm, density = 2.7 g/cc), was fed to the air stream from hopper with gravity. Particles were electrically charged with the contact among themselves and to the pipe wall. An electrodynamic sensor of ring shape with guard shields was mounted at the top of the pipe. In order to charge particles enough to the equilibrium charge, the measurement point was set to 4.7m away from the feed point.

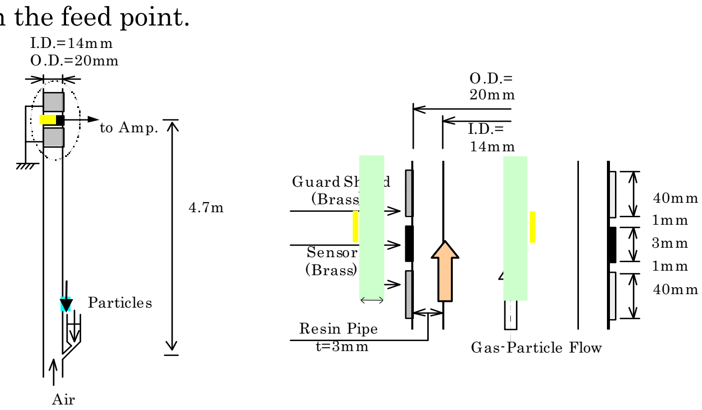
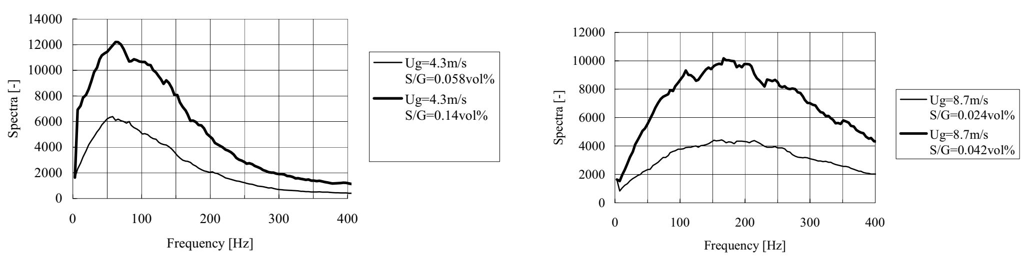


Fig. 7. Experimental Rig and Sensor's Detail.

Experiments were carried out in different gas velocities and particle flow rates. The data from the sensor were recorded and Fourier transformed. The shape of the spectra obtained the experiments shows that the shape was preserved in case of many particles. It was also confirmed that peak frequency of the spectra moves to higher frequency according to increase of gas velocity and peak height of the spectra increases according to increase of particle flow rate (Figs. 8(a) and (b)).



(a) Gas Velocity = 4.3 m/s (b) Gas Velocity = 8.7 m/s

Fig. 8. Examples of Experimental Results of Spectra from Electrodynamic Sensor Signal.

Results of peak frequencies are plotted with gas velocities and peak heights with particle flow rates in Fig. 9. Linear relations are observed and sensitivity of electrodynamic sensor was confirmed.

(a) Velocity vs Peak Frequency (b) Particle Flow Rate vs Peak Value

Fig. 9. Electrodynamic Sensor’s Sensitivity to Velocity and Particle Flow Rate.

2.4 Input Circuit for Electrodynamic Sensor

Above discussions about the electrodynamic sensor's signal are realized by the soundness of amplification of signals from the sensor. We can observe signals as long as wires are connected but correct signals for the desired purpose can not be measured without correct treatments. Any input circuit can be applied for any sensor and there are various combinations (Fig. 10). For a Faraday cage of a cup shape, a capacitance input is normally used as an input circuit because the amount of electrical charge carried by the object can easily calculated by the voltage of the sensor and the capacitance. Guessing from many papers dealing an electrodynamic sensor show the signal of both polarities, a resistance input circuit or a mixed input might be used generally.

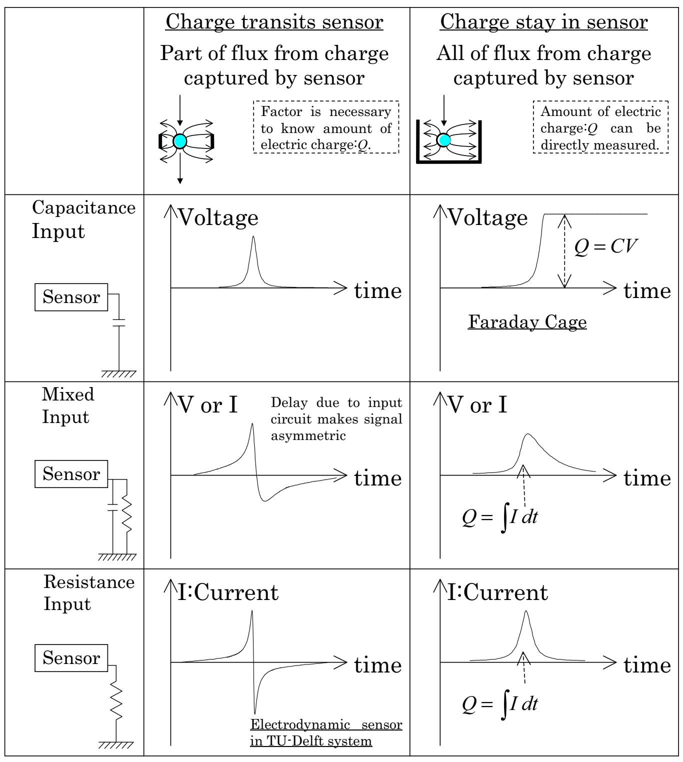


Fig.10. Signal from Sensor in Combination of Sensor Shapes and Input Circuits.

We applied the combination of an electrodynamic sensor and a resistance input with impedance of zero for a tribo-electric tomography system. The input circuit we use is shown in Fig. 11. The first stage is a current-voltage converter and the second stage is a voltage amplifier. From the concept of a virtual ground of operational amplifier, the electrodynamic sensor is equivalent to be connected to the ground and its electrical potential equals to zero. An electrical current flows between the electrodynamic sensor and the ground according to the time derivative of induced electrical charges on the sensor. Since the electrodynamic sensor's signal is an electrical current essentially, we applied a current-voltage converter as the first stage of input circuit and make sensor's electrical potential to zero. The second stage is a voltage amplifier.

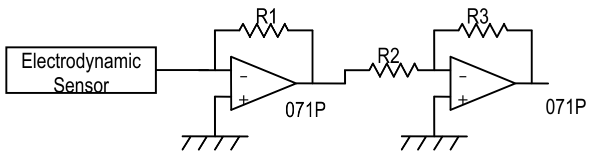


Fig. 11. Input Circuit for Electrodynamic Sensor.

We used 10k ohm, 10k ohm and 22M ohm for R1, R2 and R3, respectively. Total gain of this amplifier is 2.2×10^7 volt /ampere. The gain of the amplifier depends on the target's electrical charges we want to measure. The capacitance of the electrodynamic sensor and R1 form the time constant and change the original symmetric shape of the current into asymmetric one. This must be avoided for correct Fourier transform. Firstly the resistance for R1 must be selected, so that the time constant would not affect the electrodynamic signal. It depends on the electrodynamic sensor's capacitance and the object's velocity. Then the gain of the second stage amplifier must be chosen considering the electrodynamic signal's intensity and the input range of an AD-converter. This restriction for the first stage amplifier is the reason why this amplifier dares to use two stages of op-amp. A single stage of amplifier using 22M ohm for R1 showed better signal noise ratio but capacitance of the electrodynamic sensor and 22M ohm brings a non-negligible time delay and signal became asymmetric. Therefore we abandoned single stage amplifier and applied the two stages one. We used an A-D converter of 2.5 V input range with 10 bit resolution and the sensitivity of this system is calculated $2.5 / (2^{10}) / (2.2 \times 10^7) = 1.1 \times 10^{-10} = 0.11$ nA. In actual measurement after the best possible shielding, about from twenty to thirty least digits are masked with the noise components. Therefore, detectable electrical current from the electrodynamic sensor is estimated at the order of nA.

3. Tribo-Electric Tomography System

3.1 Description of Tribo-Electric Tomography System

Figure 12 shows details of the tribo-electric tomography system developed in TU-Delft.

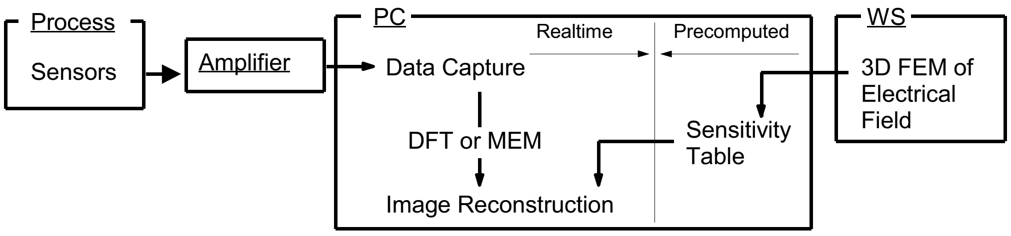


Fig. 12. Schematic Diagram of Tribo-Electric Tomography System.

The electric charges of the object are measured with electrodynamic sensors. The induced electric currents from the sensors are so small that they are amplified and captured to computer. The data are transformed into intensity spectra using discrete Fourier transform (DFT) or maximum entropy method (MEM). With these intensity data of the spectra, image is reconstructed by linear back projection (LBP) algorithm in real time measurement. Sensitivity of each sensor to each pixel was previously calculated by solving electrical field by FEM and saved as a table. LBP algorithm reconstructs image using this table.

The images measured by this system (Fig. 1(b)) are shown in Fig. 13. The position of the particles was restricted with the pipe. The sand (average diameter = 270 μm, density = 2.9 g/cc) was used. The sand was tribo-electrically charged naturally with contact among themselves or to the feeder's wall and no special charging equipment was used. Using the image reconstruction algorithm, position of the electric charge was detected as the probability of existence in each pixel. Values of probability of the pixels were normalized with the highest value among them and shown as images. Locations of the electric charges are marked as a small circle. The result when electric charges were placed in the center is the left figure and the result of off-center is the right one.

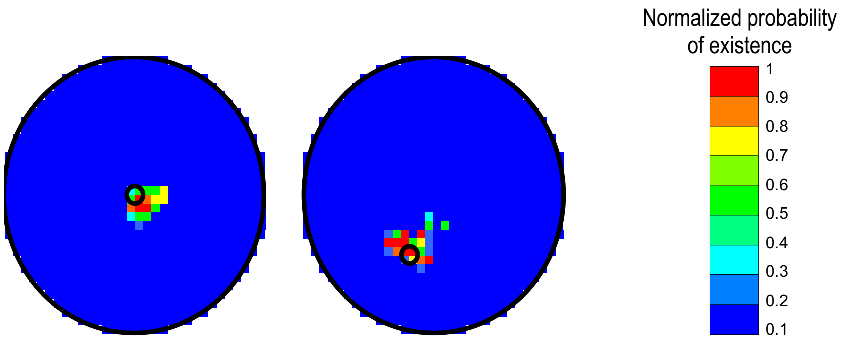


Fig. 13. Reconstructed Image by Tribo-Electric Tomography System.

3.2 Simulation of Sensor for Tribo-Electric Tomography System of More Sensors

A pipe of 100 mm diameter and 600 mm length was assumed and the electrical field inside of the pipe was solved. For an 8 sensors system, we can take 36 mm for electrodynamic sensor's horizontal length but only 8 mm are available for the length in 32 sensors system. In order to compensate decrease of signal intensity from the sensors for 32 sensors system, the sensors are extended to vertical direction to be same surface area as an 8 sensors system (Fig. 14). Cylindrical boundary was defined and electrical fields were solved as mentioned above.

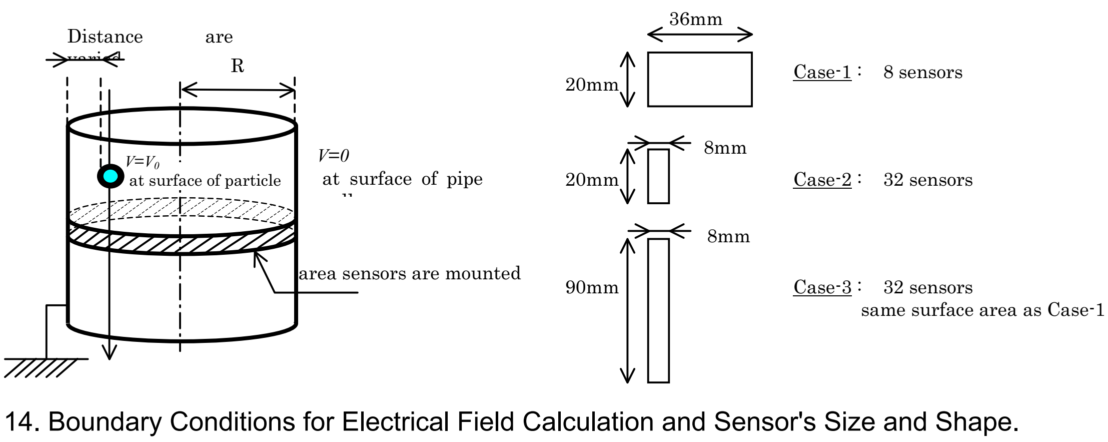
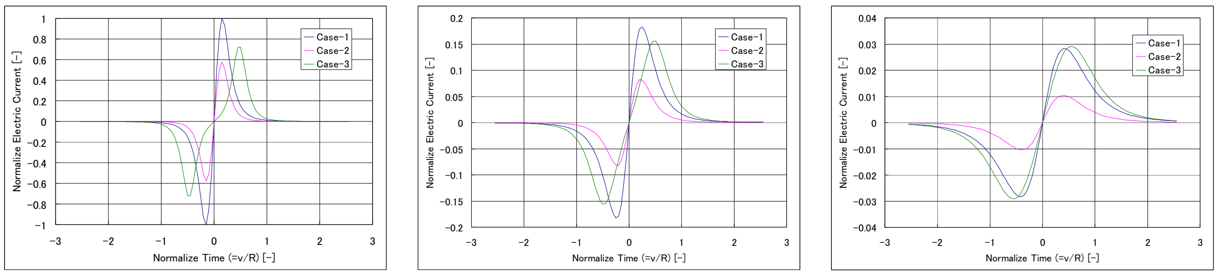


Fig. 14. Boundary Conditions for Electrical Field Calculation and Sensor's Size and Shape.

The amount of induced electrical charges becomes larger when electrical charges exist closer to the sensor or surface area is larger. An electrically charged particle was placed from the sensor at the distance of 10 mm (20 % of the radius of the pipe) and this particle was assumed to move parallel to axial direction. Electrical current from the sensor, which is equivalent to the time derivative of induced electrical charges on the sensor, was calculated. The distance was varied from 10 mm to 20 mm and 40 mm and the sensor’s shape was changed from case 1, 2 and 3. Case 1 represents an 8 electrodynamic sensors system we have been using. Case 2 represents a 32 sensors system keeping sensor's axial length same. Case 3 shows an improved 32 sensors system extending sensor's axial length and keeping sensor's surface area same as an 8 sensors system. Case 1 with the electrically charged particle at 10 mm was regarded as a base case and values of other cases were normalized with this value. The calculated results are shown in Fig. 15. Figure 15(a) shows particle exists at 10 mm distance, 15(b) at 20 mm and 15(c) at 40 mm.



(a) distance = 10 mm (b) distance = 20 mm (c) distance = 40 mm

Fig. 15. Simulation Results of Different Sizes of Sensors in Various Distances.

Comparing case 1 and 2 among the three figures, electric current signal from the electrodynamic sensor decreases according to the decrease of surface area of the sensor. The time from peak to peak remains same in case 1 and 2. On the other hand, comparison case 1 and 3 shows that keeping sensor of the same surface area can prevent decrease of the signal from electrodynamic sensor especially when particle and sensor in 40 mm of distance where signals are weak.

On the other hand, length of the sensor changes the signal’s characteristic. Time between peaks changes significantly when charged particle passes through near electrodynamic sensor. The time does not change so much when particle and sensor are far. Length of the sensing zone extends according to the length of electrodynamic sensor. Signal from electrodynamic sensor is the time derivative of electrical flux captured by the sensor. When sensing zone is too long in flow direction, all electrical flux from the particle in flow direction is captured by the long sensor. Thus, the time derivative of captured flux in flow direction increases or decreases only inlet and outlet of the sensing zone. No change of the time derivative in the middle and the sensor becomes senseless near the center. This can be observed a green line of case 3 in Fig. 15(a) and it is clear that electrodynamic signal of the case consists of two signals. Difference between case 1 and 3 in Fig. 15(c) is small. When particle exist far from the wall, the electric flux spread widely in the pipe wall and all of the electric flux is not captured by the sensor of 90 mm whose length is close to the diameter of the pipe. This change of signal shape indicates a possible advantage of using wavelet transform instead of Fourier transform to detect particle distance from the sensor. Signal strength decreases according to increase of distance between particle and sensor in every case. This decrease is relieved in the sensor of case 3 comparing to that of case 1.

4. Conclusion

An electrodynamic sensor and a Faraday cage were compared as the sensor for a tribo-electric tomography system. Combinations of input circuits and sensors were summarized. A tribo-electric tomography system with one stage of electrodynamic sensors needs Fourier transform to extract intensity information and this method can not transform correctly when frequency of the signal is changed due to the time delay caused by sensor's capacitance and input resistance. Design of the amplifier for a tribo-electric tomography is restricted with this and the circuit for this amplifier was described.

Increase the number of the electrodynamic sensors brings decrease of the signal intensity due to decrease of the surface area. Changing the design of electrodynamic sensor, extending the sensor to axis direction, can compensate this problem and is necessary to increase the number of sensors. However, it brings change the shape of electrodynamic sensor's signal and its sensitivity to the distance between particle and sensor.

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