Adaptive EMD based induction signal extraction of electrostatic sensor for particle velocity measurement

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Abstract. As the fluid movement, particles transporting in the pipeline will produce electrostatic charge. The electrostatic induction signal has been widely applied in measuring the flow parameters of pneumatic conveying due to its symmetry characteristic and simplicity. However, due to the weak signal and the complexity of the particles in the flow process, the electrostatic signal is easy to be disturbed by the environment, which affects the accuracy of particle flow parameter measurement. In this paper, an adaptive EMD method for extracting electrostatic induction signals of gas solid two-phase flow is proposed. The real IMF components and the IMF components which belong to noise are decomposed adaptively. Then according to the correlation coefficient of autocorrelation function, the corresponding IMF components are selected to reconstruct the electrostatic induction signal. The results show that in the gas-solid two-phase flow experiment, compared with the measurement signals, the mean relative standard deviation of cross-correlation velocity is reduced from 2.87% to 2.61%. This study is conducive to the accurate measurement of gas-solid two-phase flow parameters and provides an effective help for the electrostatic signal analysis of gas-solid two-phase flow.

1. Introduction
During the pneumatic conveying, the solid particles become complicated with the movement of the fluid in the pipeline. At present, the inner flush-mounted electrostatic sensor, with simple structure and good wear resistance, is widely used in particle electrostatic measurement, as shown in figure 1. The measured signal includes induced charge signal and transferred charge signal [1][2]. Through comparative experiments, C Wang et al. found that the induced charge signal and the transferred charge signal show different characteristics after charge amplifier circuit, which can be effectively distinguished in the frequency domain [3]. But in the time domain analysis, the upper and lower wave amplitude of the induced charge signal is equal, and the overall signal shows zero-mean characteristic. The flow state in the sensitive area of the upstream and downstream electrodes conforms to the solidification flow pattern hypothesis, so combining with the cross-correlation technique it has formed an important particle velocity measurement in gas-solid two-phase flow. In order to accurately extract the induced charge signal generated by the electrode and remove the transferred charge signal and the environmental common mode interference noise, effective signal noise reduction processing is necessary. In recent years, the noise reduction method based on empirical mode decomposition (EMD) is applicable to process nonlinear and non-stationary signals and is widely used in electrostatic signal analysis of gas-solid two-phase flow [4][5][6].
In this paper, an adaptive EMD based on autocorrelation function method for extracting electrostatic induction signals in gas-solid two-phase flow is proposed. The IMF component is automatically selected to reconstruct the induced charge signal from the electrostatic sensor. This effort aimed to provide a novel way to investigate the electrostatic signal of gas-solid two-phase flow.

Figure 1. Structure of inner flush-mounted electrostatic sensor

2. Experimental platform and measurement system
Referring to figure 2, the gas-solid two-phase flow experimental platform in Tianjin University is composed of the air compressor, the gas holder, the pump, the desiccant air dryer, the pneumatic control valve, the screw feeder, the conveying pipe, the receiving tank, the hopper and so on. The gas-solid two-phase flow measurement system by electrostatic method is shown in figure 3. It is composed of two kinds of electrostatic sensors, the signal conditioning circuit, the data acquisition card and the data processing equipment (PC). The solid particles used in the experiment are quartz powders with a density of 2.65 g/cm$^3$ and an average particle diameter of 100 $\mu$m. Both of the electrode groups of two electrostatic sensors are two annular electrodes with a width of 6 mm and an upstream and downstream distance of 50 mm.

Figure 2. Schematic diagram of the gas-solid two-phase flow experimental platform in Tianjin University

3. EMD signal extraction principle based on autocorrelation function
A theoretical model of induced charge on the inner flush-mounted electrode is built in the simulation software COMSOL based on the finite element method [7]. It is found that despite of the difference of the particle velocities and the location, the amplitude of the induced current is equal and the overall signal presents a zero-mean characteristic. The characteristics of the induced charge signal can satisfy the condition of EMD decomposition. The improperly selected IMF components lead to ineffective signal extraction or the loss of useful information. Based on autocorrelation function, the EMD signal extraction method is as follows. (1) Calculate the autocorrelation function of each IMF component and the sensor output measurement signal. (2) Calculate the correlation coefficients between the autocorrelation function of each IMF component and the sensor output measurement signal. To avoid
removing small but real IMF components, autocorrelation functions need to be normalized. The real IMF components can be effectively distinguished from the IMF components belonging to the high-frequency noise or the low-frequency charge transfer signal, and the electrostatic induction signal can be reconstructed.

The autocorrelation function of the original signal is $R_x$, the autocorrelation functions of selected IMF component are $R_{IMF1}, \cdots, R_{IMFK}$ (IMF1, IMF2, …, IMFK are selected corresponding IMF component). The autocorrelation function is calculated as,

$$R(m) = \frac{1}{n-1} \sum_{i=1}^{n-1} x(i)x(i+m)$$

(1)

Where $R(m)$ is the autocorrelation function, $m$ is the time delay, $x(i), x(i+m)$, are the $i$th and the $i+m$th moment signal sampling value, respectively. $n$ is the number of sampling numbers. The autocorrelation function is normalized, then the correlation coefficient of $R_{IMF1}, \cdots, R_{IMFK}$ and $R_x$ is calculated as,

$$\rho(j) = \frac{\sum_{i=1}^{n-1} R_{IMF}(i)R_x(i)}{\sqrt{\sum_{i=1}^{n-1} R_{IMF}^2(i) \sum_{i=1}^{n-1} R_x^2(i)}}$$

(2)

When $\rho(j)$ is greater than 0.4, it is considered that the corresponding IMF component has a good correlation with original signal and should be preserved [8].

4. Experiment and analysis

The experiment was carried out on the gas solid two-phase flow experiment platform of Tianjin University. Under the different solid mass flow rates and superficial gas velocities, the signal measured by the inner flush-mounted electrostatic sensor is decomposed and reconstructed with the adaptive EMD method. The sampling rate is 20 kHz, the integration time is 0.25s and the sampling time is 60s. The reconstructed upstream and downstream electrostatic induction signals are used for cross-correlation velocities. The cross-correlation velocities obtained as shown in figure 4.

![Figure 4. Cross-correlation velocities under different operating conditions](image-url)
It can be seen from figure 4 that the variation law of particle velocity can be well characterized whether the cross-correlation velocity is obtained from upstream and downstream measurement signals or obtained from adaptive EMD method. The mean relative standard deviation of the signals can be obtained under all flow conditions. The mean relative standard deviations of correlation velocity obtained by measurement signal and adaptive EMD are 2.87% and 2.61% respectively.

5. Conclusions
In this paper, a method based on adaptive EMD to extract electrostatic induction signal in gas-solid two-phase flow is proposed. Based on the symmetry of the electrostatic induction signal, according to the correlation of autocorrelation function between the signal components obtained from the EMD decomposition and the original sensor output measurement signal, the appropriate signal component is adaptively selected to restructure the electrostatic induction signal.

The mean relative standard deviation of cross-correlation velocity decreased from 2.87% to 2.61%. The proposal method improves the stability of measurement. It is helpful for the electrostatic signal analysis of the gas-solid two-phase flow.

References
[1] Ma J and Yan Y 2000. Design and evaluation of electrostatic sensors for the measurement of velocity of pneumatically conveyed solids. Flow Measurement and Instrumentation. 11 195-204
[2] Qian X, and Yan Y 2012. Flow measurement of biomass and blended biomass fuels in pneumatic conveying pipelines using electrostatic sensor-arrays. IEEE Transactions on Instrumentation and Measurement. 61 1343-52
[3] Wang C, Zhang J, Zhang Y and Yan Y 2014. Representation of induced and transferred charge in the measurement signal from electrostatic sensors. In Instrumentation and Measurement Technology Conference (I2MTC) Proceedings, 2014 IEEE International. 1306-1309
[4] Lu R, Zhou B and Gao W 2009. Signal analysis of electrostatic gas-solid two-phase flow probe with hilbert-huang transform. In Electronic Measurement & Instruments, 2009. ICEMI'09. 9th International Conference on 2-486
[5] Boudraa A O, and Cexus J C 2007. EMD-based signal filtering. IEEE Transactions on Instrumentation and Measurement. 56 2196-2202
[6] Fu F, Xu C and Wang S 2012. Multi-scale resolution of pressure signal and electrostatic signal of dense phase pneumatic conveying of coal powder. In Zhongguo Dianji Gongcheng Xuebao(Proceedings of the Chinese Society of Electrical Engineering) 32 72-78
[7] Wang C, Zhang J, Zheng W, Gao W and Jia L 2017. Signal decoupling and analysis from inner flush-mounted electrostatic sensor for detecting pneumatic conveying particles. Powder Technology. 305 197-205
[8] Landis J R and Koch G G 1977. The measurement of observer agreement for categorical data. Biometrics. 159-174

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