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Statistical modeling and signal reconstruction processing method of EMF for slurry flow measurement

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According to the experimental data, an amplitude probability density function (PDF) model of the slurry flow signal is built up for electromagnetic flowmeter (EMF) by the method combining statistical analysis with numerical fitting, in order to reveal the effect of slurry noise on the flow signal and describe the features of slurry flow signal. Based on this model, a signal reconstruction processing algorithm is proposed to deal with the output signal of EMF sensor for realizing the slurry flow measurement. At the same time, the high-low voltage switching mode based square-wave excitation method is presented for EMF so as to reduce the slurry noise interferences. A slurry-type EMF transmitter is developed with a DSP chip – TMS320F28335, to implement the signal processing algorithm and control function. Finally water flow calibrations and slurry flow experiments are conducted to verify the reliability and stability of the method and system. Experimental results show that its measurement accuracy of water flow is better than 0.5%, and its steady-state volatility of paper slurry is less than 3%, and its dynamic response time is less than 4 s.

1. Introduction

Transportation of solid–liquid slurries, such as paper slurry, coal slurry and Alumina slurry over a certain distance through pipelines is very popular in industries, such as in paper mill, power station and chemical plant. It is also important to accurately measure the flow rates of these kinds of slurry flow for controlling of production process. Strictly speaking, slurry is a complex mixture, and its physical characteristics depend on many factors, including the size and concentration distributions of solid particles in liquid phase, level of turbulence, temperature, viscosity and so on. For process control, however, only the slurry flow rate, i.e., the mean velocity of the slurry flow is required to be measured. At the same time, for industrial applications, it is always hoped that a simple and single meter is selected to accomplish this task.

EMF has been successfully applied to measurement of the mean velocity of single-phase conductive fluid in various industries. And continuous efforts have also been made to measure the slurry flow using EMF because of its structural characteristic, i.e., no hindering fluid components. But there are large fluctuation and big error in slurry measurement with EMF.

The electrical double layers nearby electrodes will be destroyed when slurry solid particles scratch the electrodes of EMF during the measurement [1–4]. Thus one kind of spike-like noise is generated and called "the slurry noise". This kind of undesired signal is superimposed on the normal flow rate signal, and leads to large fluctuation in the measurement result.

For the problem of slurry measurement of EMF, some researchers and companies proposed their solutions and developed the EMF with the function of slurry flow measurement.

Yoshinori Matsunaga et al. proposed dual frequency excitation to solve the problem of occasional output

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fluctuations during slurry flow measurements [5,6]. In this EMF, the magnetic field excitation coils were driven by square wave excitation signal of a low frequency (about 6.25 Hz) and a high frequency (about 75 Hz or 112.5 Hz). The electromotive force signal detected by the electrodes (sensors of EMF) was separated into a low-frequency signal excited by low-frequency excitation and a high-frequency signal excited by high-frequency excitation. The separated signals were processed to obtain the flow rate.

Ichiro Wada developed an EMF with two magnetic field generating units that were excited at different time intervals [7]. The first generating unit applied a square wave of 4–8 Hz to the fluid and induced the first signal of the EMF. The second generating unit applied a square wave of 25–35 Hz to the fluid and induced the second signal of the EMF. The two signals were filtered and calibrated according to the flow state.

Evren Eryurek et al. introduced a single-frequency square-wave EMF with wavelet processing method to eliminate slurry noise [8]. The EMF flow rate signal was subtracted from its one-cycle delayed signal. And the positive and negative spikes were removed from the subtraction result. Then wavelet transformation was performed to decompose and filter the signal. Finally the neural network was utilized to calculate the flow rate.

The above solutions reduced slurry noise effect to different degrees, and their developed meters also made it possible that EMF could measure the slurry flow rate. But they did not build the signal model of slurry flow which was the basis of signal processing. Obviously, there is a large room for further research to be carried out with signal processing method and new magnetic field excitation techniques.

In addition, some scholars studied on measurement of the concentration and particle size of the slurry fluid by EMF. Peters and Shook carried out slurry experiments with a sine wave excitation EMF. They found that the relative fluctuation of slurry flow velocity was relevant with the solid concentration and particle type, through the theoretical analysis of experimental data [4]. Halit Eren and James Goh conducted slurry experiments with a square wave excitation EMF, and discovered that the signal frequency components and relative amplitude were related to particle type and slurry concentration [9–11]. Jing-Yu Xu et al. used the electrical resistance tomography method to obtain the slurry particle volume ratio [12]. All the research above only focuses on the influences of solid material and flow pattern on EMF measurement. They thought that the fluctuations of slurry flow could be removed by time-average method. If the time requirement for signal processing is not considered, it may be able to eliminate the interference of slurry by the long time average. However the industrial instruments have the requirement of real time, e.g., the measured value must be refreshed within two seconds. It is impossible to remove the effect of slurry noise in such a short average time. Moreover, the raw flow signal is always in fluctuation caused by slurry noise and the flow rate may change at any time.

In order to reveal the effect of slurry noise on the flow signal and to describe the features of slurry flow signal, an amplitude model of the slurry flow signal is built up by the method combining statistical analysis with numerical fitting, according to the experimental data of paper slurry. Based on the model, a signal reconstruction processing method is proposed to deal with the output signal of EMF sensor. This method reconstructs de-noised slurry flow signal from amplitude demodulation result. It avoids filtering slurry noise directly in traditional signal filtering routine, and simplifies the difficulty and complexity of removing non-stationary slurry noise.

To reduce the impacts of slurry noise interferences, a square-wave excitation method is presented for EMF based on high-low voltage switching mode. A slurry-type EMF transmitter is developed with a DSP chip – TMS320F28335 to realize the signal processing algorithm and control function. Finally water flow calibration and slurry flow experiment are conducted to verify the reliability and stability of our method and system.

2. Modeling of slurry flow signal

During slurry flow measurement, EMF outputs flow signal as well as many other kinds of noises. Spectrum analysis shows that slurry interference is mainly concentrated in low frequency region, and its amplitude decreases as frequency increases, having the 1/f characteristic. This is because slurry interference arises as a result of sudden change in electrode polarization voltage, which used to be changing slowly [5–6].

Thus slurry interference superimposed on the flow signal has the exponential decaying amplitude after a step transition, and its spectral characteristic approximates the 1/f distribution. Therefore, some slurry-type EMFs adopt the high frequency excitation mode to reduce slurry noise.

2.1. Slurry flow measurement experiments

The slurry noise is known as low-frequency interference, but the model of the slurry flow signal of EMF is not built up in studies above. Since the generating time and amplitude of slurry interference are random, and its generating mechanism is complex, it is difficult to establish the slurry signal model through mechanism analysis. Therefore the statistical amplitude models of water flow and paper slurry flow signals are built by numerical fitting method based on water flow and paper slurry flow experiments, so as to reveal their distribution pattern, and provide theoretical basis for further signal processing.

In order to collect output signal of the EMF sensor for signal modeling, a series of experiments on water and paper slurry flow were conducted in Chongqing Chuanyi Automation Co., Ltd. in Chongqing City, China. The experiment setup is shown in Fig. 1. It consists of a mixing tank, a slurry pump, pipelines, a reference EMF, a test EMF, a diverter valve and a regulating valve. The mixing tank is 1.42 m long, 0.5 m wide and 4.25 m high; its volume is 300 L. The diameter of pipelines is 25 mm. The maximum flow velocity in measuring pipe is 2.3 m/s. A Toshiba's IF600 EMF with 24 Hz excitation frequency is selected as