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Practice article

Echo signal envelope fitting based signal processing methods for ultrasonic gas flow-meter

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HIGHLIGHTS

- The echo signal envelopes under different flow rates are analyzed.
- Echo signal envelope fitting based signal processing methods are proposed.
- The best one of three kinds of signal processing method is selected.
- An ultrasonic gas flow-meter is developed with the DSP and FPGA.
- The gas flow calibration experiments are conducted.

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ABSTRACT

The echo signal of the ultrasonic gas flow-meter is difficult to locate, and the computation of signal processing methods proposed by others is extensive which affects the meter's real-time performance. Aiming at solving these problems the echo signal envelopes under different flow rates are analyzed. And three kinds of signal processing methods based on echo signal envelope fitting are proposed. The shape of the echo signal remains the "approximate spindle shape" as the flow rate increases, and the envelope gradient of the middle parts of the upper envelope's rising section and the lower envelope's falling section remains the same at different flow rates, so the mathematical models of the two sections are established to obtain the envelope gradient curves of the two sections. With the envelope gradient curves, the ranges of envelope and peak points that linearly distributed are obtained. The least squares fitting is performed on those peak points to obtain two feature straight lines for respectively representing the upper envelope's rising section and the lower envelope's falling section. According to the spatial characteristics of the feature straight lines, the points on the feature straight lines are selected as the feature points for quickly locating the echo signal. According to the offline verification and comparison, the best one of three kinds of signal processing methods is selected, and realized on the hardware system of the two-channel ultrasonic gas flow-meter. The transmitter of two-channel ultrasonic gas flow-meter is developed based on FPGA & DSP dual core structure. It utilizes the parallel processing capacity and logic control ability of FPGA to realize the controlling of the high-speed ADC & DAC and the storage of the data. At the same time, it adopts the high-speed computing capacity of DSP to implement the digital signal processing method. The gas flow calibration experiments were carried out in a national accredited testing agency to verify the effectiveness of the signal processing methods and system. The experimental results show that the improved signal processing method based on echo signal upper and lower envelope fitting can quickly and accurately locate the echo signal. And the measurable range of the ultrasonic gas flow meter based on this signal processing method is broadened to 10 m^3/h to 1,300 m^3/h, and the turndown ratio is broadened to 1:130.

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1. Introduction

Ultrasonic gas flow meter has many advantages, such as large turndown ratio, high accuracy, no pressure loss and so on, especially for large diameter gas flow rate measurement [1,2]. At present, the time difference method, which measures the gas flow rate by calculating the difference of the downstream and upstream

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propagation time, is widely used on the ultrasonic gas flow meter [3,4]. Since the energy of ultrasonic wave is seriously weakened when it propagates in the gas flow, the signal-to-noise ratio of the echo signal is low [5,6]. As the flow rate increases, this problem becomes worse, and it is difficult to locate the echo signal for accurately determining the propagation time [2,7]. And when the flow rate is small, the displacement of the echo signal caused by the change of flow rate is small, so the signal processing method should possess high resolution and stability.

In order to locate the echo signal for determining the propagation time, some signal processing methods were proposed by some scholars. These methods can be mainly classified as two types as follows.

The first type is to detect the starting point of the echo signal to locate the echo signal. Yan-Dan Jiang et al. put forward a signal processing method based on the mathematical model of echo signal [8]. In the method, the echo signals were processed offline to establish the mathematical model of the echo signal. And when measuring the flow rate, the sampled echo signals were compared with the mathematical model to detect the starting point of the echo signal for locating the echo signal. Ze-Hua Fang et al. proposed a signal fitting method based on artificial fish swarm algorithm combining with particle swarm optimization (AFSA-PSO) [9]. Firstly, AFSA was used to search for all possible solution spaces. Then, a feasible solution extraction strategy was proposed to extract the local optimal solution in every space. Finally, PSO was employed to further process the local solutions to obtain the accurate USO (ultrasonic signal onset). Although the first type of methods can utilize adequate information of the echo signal. But the detected position is the starting point of the echo signal. The amplitude of the starting point of the echo signal is low, and it is susceptible to noise interference and difficult to be distinguished. So the measurement range and accuracy of this type of methods are not ideal.

The second type is to find a feature point of the echo signal to locate the echo signal. P. Brassier et al. proposed a signal processing method based on the cross-correlation algorithm [10]. However, due to the large amount of calculation of the cross-correlation algorithm, it was difficult to ensure the real-time performance of the system. Zi-Wen Shen et al. proposed a signal processing method based on the rate of the echo signal energy [11]. Firstly, the echo signal was filtered to obtain the peak points of the echo signal. The square of each peak point value was calculated as the energy of each peak point, and fitted to obtain the echo energy envelope. Then, the energy gradient of each peak point on the echo energy envelope was calculated and fitted to obtain the echo energy gradient curve. Finally, according to the echo energy gradient curve, a threshold was set to distinguish the feature point. In the actual measurement, the echo energy gradient curve should be fitted in real time, and the feature point was determined according to the preset threshold. The method is complicated because of many steps. And a large amount of calculation will affect the real-time of the system. Wei Wang et al. put forward a signal processing method based on variable threshold and zero crossing detection [12,13]. In the method, the distribution of the peak points of the echo signals was studied, and a threshold which varied with the amplitude of the maximum peak point of the echo signal was set. The feature point can be distinguished with the variable threshold to locate the echo signal. The method was realized on the system with the DSP (Digital Signal Processor) and FPGA (Field Programmable Gate Array) dual cores, and achieved a good result [14]. But as the flow rate increased, the positions of the peak points were shifted, so the measurement range of this method was limited. The detected position of this type of methods is a feature point of the echo signal. The feature point can be easily distinguished, and can well reflect the displacement of the echo signal caused by the flow rate. Therefore, the second type of methods could reach high accuracy and be widely used. However, the echo is unstable at large flow rates, which results in large measurement error. The measurement range of this type of methods is from 1.06 m/s–30 m/s.

In order to improve the real-time performance and the measurement range of the system, the echo signal envelopes under different flow rates are studied. It is found that the shape of the echo signal is "approximate spindle shape" at different flow rates, and the rising section of the upper envelope and the falling section of the lower envelope remains the same, just like moving along the X-axis in parallel as the flow rate increases. Therefore, the points on the two sections could be selected as the feature points. But in the actual measurement, the echo signal envelopes should be fitted in real time, and there would be large amount of calculation. At the same time, it is also found that the peak points covered by the middle parts of the upper envelope's rising section and the lower envelope's falling section are approximately distributed in two straight lines. The least squares fitting is performed on those peak points to obtain two feature straight lines for respectively representing the upper envelope's rising section and the lower envelope's falling section. Therefore, selecting the points on the two feature straight lines as the feature points can not only reflect the displacement of the echo signal caused by the flow rate, but also reduce the amount of computation. According to the spatial characteristics of the feature straight lines, three kinds of signal processing methods based on echo envelope fitting are proposed to quickly and accurately locate the echo signal. With the offline verification and comparison, the one with the best effect of the three kinds of signal processing methods is selected, and realized on the hardware system of two-channel ultrasonic gas flow-meter based on the DSP and FPGA. The gas flow calibration experiments are carried out in a national accredited testing agency to verify the effectiveness of the signal processing methods and system.

2. Signal processing methods

2.1. Echo signal envelope study

The echo signal envelopes are studied in order to find a stable feature point to accurately locate the echo signal. It is found that the shape of the rising section of the upper envelope and the falling section of the lower envelope remains the same at different flow rates, just like moving along the X-axis in parallel with the flow rate increasing. To illustrate this phenomenon more clearly, 50 sets of sampled echo signals at different flow rates (0 m^3/h, 200 m^3/h, 400 m^3/h, 600 m^3/h, 800 m^3/h and 1000 m^3/h) with a two-channel ultrasonic gas flow-meter. Then, the echo signals are filtered, averaged and normalized, and with the help of the curve fitting tool of MATLAB, the positive and negative peak points of the echo signal are separately fitted to obtain the echo signal envelopes of different flow rates. The specific steps are described as follows.

(1) 50 sets of echo signals are sampled at 0 m^3/h flow rate. And the fourth-order Butterworth band-pass filter is used to filter the echo signals. The frequency of the echo is 200 kHz. So the pass-band range of the filter is set from 180 kHz to 220 kHz.

(2) The same position of the filtered echo signals are summed, and then divided by 50 to obtain the average echo signal.

(3) The maximum peak value of the average echo signal is found by comparison, and each position of the average echo signal is divided by the maximum peak for obtaining the normalized echo signal.

(4) With the help of the curve fitting tool of MATLAB, the positive and negative peak points of the normalized echo signal are separately fitted to obtain the echo signal envelope of 0 m^3/h flow rate.

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