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Echo energy integral based signal processing method for ultrasonic gas flow meter

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ABSTRACT

Ultrasonic gas flow meter possesses unique measurement advantages, and is especially suitable for natural gas measurement of large diameter gas pipelines. It is very important to obtain the accurate transit-time of ultrasonic signal for ensuring the measurement accuracy of ultrasonic gas flow meter. However, it is difficult to find stable feature points for determining the transit-time in ultrasonic gas flow meter signal processing. Aiming at this problem, the echo energy gradient is analyzed from the point of the echo energy integral in this paper, an echo energy integral based signal processing method is proposed, and corresponding parameter selection is put forward. First of all, the FCE (fixed cumulative energy) value is set as a standard, and the area of the EES (echo energy signal) rising section is integrated, that is, the echo energy in this period of time is accumulated. When the cumulative energy value exceeds the FCE value, the end position of the FCE value is taken as the feature point. Then the ultrasonic transit-time is obtained, and the gas flow rate is calculated. This digital signal processing method is implemented in real-time in the digital system with the FPGA (Field Programmable Gate Array) and the DSP (Digital Signal Processor) as the double cores, and the gas flow calibration experiments are conducted to verify the effectiveness of the proposed digital signal processing method.

1. Introduction

Ultrasonic gas flow meter as a device to detect gas flow in the chemical industry, metallurgy, natural gas trade and other fields, especially it plays an increasingly important role in the gas transmission and energy saving [1,2]. It is mainly divided into a time difference method, a phase difference method, a frequency difference method and Doppler method according to measurement methods of the ultrasonic flow meter. Among them, the time difference method is used to measure the velocity and flow rate of the gas by calculating the ultrasonic transit-time of the downstream and upstream, it is the most commonly used and most effective measurement method, which has less error caused by the change of temperature than that of other measurement methods [3,4]. For the ultrasonic transit-time, the time when the transmitting transducer emits the ultrasonic is the starting moment of the transmit-time. This moment is artificially controlled. The time when the receiving transducer receives the echo signal is the ending moment of the transmit-time. It is difficult to determine this moment accurately for various reasons.

Due to the damping characteristic of the ultrasonic transducer, the energy of the ultrasonic signal attenuates seriously when it propagates in the gas, and as the gas velocity increases, it will generate a corresponding path offset to further weaken the energy [5,6], which makes the echo signal amplitude weaker and leads the SNR (signal-to-noise ratio) decrease. If the starting point of the echo signal is used as a feature point, it is easily submerged by noise interference; if the maximum peak point of the echo signal is used as a feature point, its position fluctuates greatly under large flow rate conditions, and it is difficult to locate accurately. Therefore, it is necessary to find a stable feature point on the echo signal to determine the transit-time, so as to measure the gas flow accurately.

In order to obtain the stable feature point, scholars have studied a variety of signal processing methods from different perspectives. From the perspective of the echo amplitude, scholars put forward a signal processing method based on a fixed threshold. When the ultrasonic signal was sent out, the timing was started at the same time. By setting a fixed threshold, when the echo amplitude was greater than this threshold, the timing was stopped. This moment

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was as the receive time of the echo signal, and this period of time was used as the transit-time. T. Kobayashi et al. implemented this fixed threshold method by means of hardware circuits [7]; R. Bates et al. referred to the software implementation of this fixed threshold method [8]. Qiang Chen et al. proposed a double threshold method based on analog signal measurement [9]. When the received echo signal met the double threshold condition, the timing was stopped and the transit-time was calculated. However, the echo amplitude is easily affected by noise and other interference, which makes the measurement accuracy and fault tolerance of the method poor. From the perspective of the echo energy gradient, W. Freund et al. proposed a signal processing method based on the energy mutation point [10]. According to the pattern that the echo energy gradient first increased and then decreased during the entire propagation, it could determine the transit-time by detecting the critical change point of the energy gradient. However, the method did not disclose the key techniques, for example, the time interval selection of the sliding window. Zi-Wen Shen et al. proposed a signal processing method based on the energy gradient [11]. It calculated the key threshold point on the energy gradient curve, and then backtracked to the original signal to find the corresponding zero crossing as the feature point. As the threshold needed being set in advance, its implement was relatively complex. Lei Tian et al. proposed a signal processing method based on energy peak fitting of echo [12]. The relationship between echo energy and echo energy gradient was analyzed, and the range of the optimal echo energy point location was obtained. One echo energy point within the range was selected, and the value of this point was regarded as a reference to locate the four nearest echo energy peak points for linear fitting. The echo energy point corresponding to the energy value on the fitting straight line was found as the feature point. This method has achieved good experimental results. From the viewpoint of echo peak point distribution, Wen-Jiao Zhu et al. proposed a signal processing method based on variable ratio threshold and zero-crossing detection [13]. The distribution of echo peak points was analyzed, and the corresponding feature points were obtained by setting the threshold value that could separate the feature peak from other peaks. It was used to calculate the transit-time. With the flow rate increasing, however, the peak offset of the echo signal will be aggravated, and the maximum measurable flow of the method is limited. From the perspective of establishing the echo signal model, Yan-Dan Jiang et al. proposed a model-based signal processing method [14]. The echo signal was preprocessed by using zero-phase filtering and ICA-R (independent component analysis with reference). The least difference between the actual filtered echo signal and the echo signal established by the model was calculated by least squares, and the echo signal initial position in the model was determined. But the measurement accuracy was not high. From the perspective of fitting the echo curve, Ze-Hua Fang et al. proposed a signal fitting method based on AFSA-PSO (Artificial Fish Swarm Algorithm and Particle Swarm Optimization) [15]. All possible solution spaces were searched by using the advantages of AFSA in fitting multi-dimensional and multi-mode objective functions, and the optimal solution to the space was searched by using PSO's high efficiency and easy-to-implement characteristic to obtain the starting position of the echo signal. This method was mainly aimed at the echo signal with serious noise pollution, and took the expense of real-time performance in exchange for enhancing anti-noise ability and improving accuracy. From the perspective of gas flow rate fusion, Long-Hui Qin et al. put forward a signal processing method based on the multipath ELM (extreme learning machine, also known as single hidden-layer feed-forward neural networks) [16]. The method was based on the minimum fusion error. The error back-propagation and the iterative adjustment of the parameters were skipped by using ELM comprehensive performance and limit learning speed, and the output weight of the path was calculated directly. It would improve the speed of training and reduce the manual intervention. It could guarantee high precision of measurement, and was insensitive to the installation position of the instrument. The simulation data given in paper had a certain guiding significance for the practical application of ultrasonic gas flow meter. From the perspective of the echo signal envelope, Lei Tian et al. proposed a signal processing method based on echo peak fitting [17]. The variation pattern of the echo signal profile was analyzed, and a few peak points in ascending phase were fitted by using the least squares to obtain an intersection of the feature line and the X-axis. This intersection was as the feature point. However, this method was insensitive to the weak changes of the signal at low flow rates, and made the measurable range smaller.

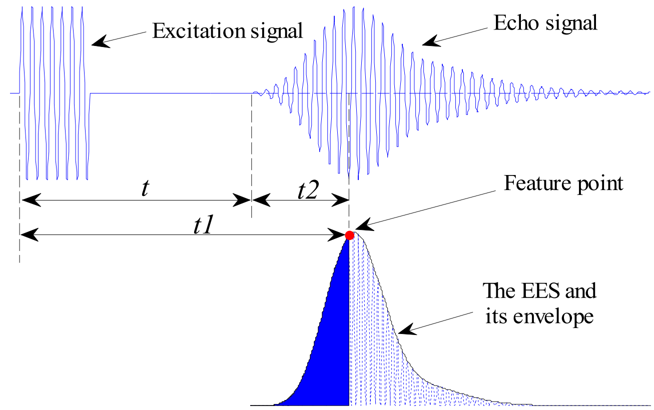

Fig. 1. Schematic diagram of excitation signal and echo signal.

Aiming at the problem that it is difficult to find the stable feature point for the echo signal, a signal processing method based on the echo energy integral is proposed from the perspective of the echo energy integral. The echo signal is filtered and normalized. The peak points of the rising section are found, and the squares of their amplitudes are treated as these points' energy. The trapezoidal area enclosed by adjacent peak points is accumulated, that is, the echo energy in this period of time is accumulated. When the cumulative energy value exceeds the FCE value, the end position of the FCE is taken as the feature point. According to the feature point, the ultrasonic transit-time between the downstream and upstream can be calculated, and the gas flow rate can be obtained. This digital signal processing method is implemented in real-time in a digital system with the FPGA and the DSP as the double cores, and the gas flow calibration experiments are conducted to verify the effectiveness of the proposed digital signal processing method.

2. Signal processing method

2.1. Principle of echo energy integral

The ultrasonic gas flow meter based on the time difference method measures the ultrasonic transit-time of the downstream and upstream channels, and calculates the time difference between them to obtain the gas flow rate. The relationship between the ultrasonic transit-time t, the excitation signal and the echo signal, as shown in Fig. 1.

The starting moment of t is determined by the emission time of the excitation signal, that is, the starting position of the excitation signal can be accurately obtained. However, the ending moment of t is difficult to accurately locate because the starting position amplitude of the echo signal is small and is susceptible to noise interference. Therefore, in the actual flow measurement, t is indirectly calculated by replacing the starting position of the echo signal with the position of the feature point.