Treatment of Underground Dust Concentration Detection Signal and FPGA Implementation

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Abstract. In view of the special environmental interference of coal mine dust concentration signal acquisition, it is necessary to analyse the characteristics and filter the noise signal mixed into the system in the process of coal dust concentration signal acquisition by sensors. Combining with the characteristics of actual coal dust concentration signal, IIR filter is designed by bilinear Z-transform method, and the IIR digital filter is implemented by using VHDL hardware description language in FPGA. Finally, the performance of the filter is verified by simulation using MATLAB and Modelsim.

1. Introduction

In the analysis and processing of collecting coal dust concentration signal, the weak signal of photoelectric sensor will be mixed with various noise signals in the process of amplification, filtering and conversion, and will be converted into digital signal together with the signal, especially when detecting low concentration coal dust, useful signal will even be submerged by noise[1-3]. The useful signal is even overwhelmed by noise. The coal dust concentration measurement system is real-time online measurement, so it avoids uploading unprocessed data to PC processing and compares software filtering algorithms that consume hardware resources, and chooses IIR wireless impulse response filtering based on FPGA [4-5].

2. Noise analysis of the measurement system

Noise is ubiquitous from the acquisition, transmission, and processing of measurement signals. The presence of noise greatly increases the difficulty of obtaining useful information from the signal. So, understanding and mastering the noise characteristics of coal dust measurement signals is the primary link in the design of filtering algorithms.

2.1 white noise

White noise is a common noise. White noise refers to a noise signal whose power spectral density is a constant value in the infinite frequency range (-∞<ω>∞), and is characterized by various noises. In general, noise with a uniformly distributed power spectral density function that exceeds the operating frequency range of the system can be considered white noise.

2.2 Gaussian noise

Gaussian noise is a type of noise in which the probability density function distribution obeys a
Gaussian distribution. The mathematical expression of the one-dimensional probability density function is 
\[ p(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-a)^2}{2\sigma^2}} \]  
(1)
a is the mathematical expectation of noise.
\(\sigma^2\) is the noise variance.

3. Digital Filter Algorithm Selection and Design

The coal dust concentration measurement system is real-time online measurement, so it avoids uploading unprocessed data to PC processing and compares software filtering algorithms that consume hardware resources, and chooses IIR wireless impulse response filtering based on FPGA.

3.1 IIR digital filtering

The cascading structure of the IIR digital filter is widely used, and has the advantage of being able to control the zero and the pole of the filter to adjust the frequency characteristics. The basic structure of the IIR digital filter is as follows.

\[ y_k = x_k \cdot c_{-6} + x_{k-1} \cdot c_{-5} + \cdots + x_{k-9} \cdot c_0 + \cdots + x_{k-11} \cdot c_5 + x_{k-12} \cdot c_6 \]  
(2)

The above formula can be calculated in one cycle, so that the data is shifted to the right by one bit before the next cycle, the original input is replaced by the next one, and the loop is sequentially executed, and the output value is finally calculated.

3.2 Design of IIR digital filter by bilinear Z-transform method

With the design experience of the mature low-pass analog filter, given the technical index \(\{\omega_p, \omega_s, a_p, a_s\}\), the normalized frequency \(\lambda\) is used, \(|K(j\lambda)|^2\) is used as the polynomial representation of \(\lambda^2\) as the independent variable, and the square and coefficient values in the polynomial are obtained according to the given conditions. Then, the obtained result is substituted into \(H(j\lambda)\) and then let \(p=j\lambda\). Convert \(|K(j\lambda)|^2\) to \(|H(p)|^2\), then find \(H(p)\) according to the party condition, and finally bring \(p = s/\omega_r\) into \(H(p)\) to get \(H(s)\).

\[ H(s) = H(p)\bigg|_{p = s/\omega_r} \]  
(3)

The next task is to map the analog filter transfer function \(H(s)\) onto the z-plane to get \(H(z)\), which results in a digital filter.
The bilinear z-transform method brings 
\[ s = \frac{2}{T} \frac{1-z^{-1}}{1+z^{-1}} \]
into the analog filter transfer function of 
the previous design to obtain the corresponding digital filter transfer function, which is

\[ H(z) = H(s) \mid_{s = \frac{2}{T} \frac{1-z^{-1}}{1+z^{-1}}} \]  

Take T=1, simplification is

\[ H(z) = 0.7588(1 + 0.9894z^{-1}) \times \frac{1 + 2.0192z^{-1} + 1.0193z^{-2}}{1 + 0.8842z^{-1} + 1.7877z^{-2} + 0.8013z^{-3}} \times \frac{1 + 1.9867z^{-1} + 0.9868z^{-2}}{1 + 1.9323z^{-1} + 0.9470z^{-2}} \]  

The characteristic curve of the obtained IIR digital filter is shown in the figure below.

![Bilinear transformation method digital filter characteristic curve](image1)

The following figure shows the coincidence signal of the system measurement signal after filtering and the additive random distribution random noise. After denoising by IIR filter, you can see from the figure. Out, there is almost no attenuation of the test signal, and it has a strong inhibitory effect on random distributed noise.

![Filtered mixed additive random noise random noise composite signal and spectrum](image2)

4. FPGA-based IIR digital filter implementation

The IIR filter FPGA program for the entire cascade consists of a top-level file, a first-stage filter file, a second-stage filter file, a third-stage filter file, and a fourth-stage filter file. The top-level file completes the combination of the four-stage cascaded filters, and the cascaded filter files complete the implementation of the entire filter [6]. After compiling in the Quartus II software, the RTL schematic is as follows.

![Cascade Structure RTL Schematic](image3)
It can be seen from Fig. 4-2 that the denoised coal dust concentration signal data is denoised by four-stage sub-filter filtering, and finally the denoising process is completed, and the processed data is output.

Figure 5. Schematic diagram of the four-stage cascade sub-filter

5. IIR digital filtering comprehensive simulation analysis
After the FPGA hardware implementation of the filter is completed, it needs to be simulated and analyzed. The synthesized single-frequency signal and white noise signal generated by MATLAB software are used as input test data. The synthesized signal and the noise signal data are stored in two files separately, and the test bench file is written, and the simulation is performed as the simulation input data when using Modelsim for FPGA simulation. The data of the Modelsim simulation output is stored in the specified file, and then the Modelsim simulation output data is analyzed and processed using MATLAB software to check whether the design filter meets the design requirements of the coal dust concentration measurement system.

The method of analysis is time domain and spectrum comparison. As can be seen from Figure 6, the FPGA simulation data is identical to the signal directly simulated by MATLAB. As is apparent from Figure 9, the synthesized single-frequency signal of the filter becomes a distinct single-carrier signal of 2000 Hz, so that the filter design satisfies the requirements.
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Figure 8. Time domain waveform before and after FPGA simulation white noise signal filter

Figure 9. Time domain waveform before and after FPGA simulation combined single-frequency signal filtering

6. Conclusion
In this paper, the source and noise characteristics of the interference noise in the simulated and filtered data of the coal dust concentration acquisition system are analyzed. In the design process of the IIR filter, the design experience of the mature low-pass analog filter is adopted, and the bilinear Z-transform method is adopted. The low-pass filter is designed by bilinear Z-transform method, and its transfer function is obtained. Then the desired digital filter system function can be obtained by mapping the transfer function of low-pass analog filter to Z plane. The FPGA implementation of the IIR digital filter is then implemented using the VHDL hardware description language. Finally, we send the noise signal and test signal into the filter for denoising, verify the performance of the filter, and complete the denoising algorithm design of the coal dust concentration data.

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