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Design and Implementation of Data Acquisition Filter for Electrical Capacitance Tomography

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Abstract

On the basis of analyzing the working principle of ECT data acquisition system and wavelet Kalman algorithm, the realization method of a new ECT data acquisition filter is proposed about the acquisition accuracy and real-time requirement of electrical capacitance tomography ECT (Electrical Capacitance Tomography) data acquisition system. The method uses the principle of multiplexing and folding structure to make the multi wavelet decomposition and reconstruction combined, parallelize high-pass filter and low-pass filter to meet the requirement of real-time. The simulation experiment results show that the processing speed of the improved ECT data acquisition filter is improved, the acquisition speed and the accuracy of the data are better than the traditional ECT data acquisition system, it provides a new filter realization method for ECT data acquisition system.

Keywords: *Electrical capacitance tomography; Data acquisition; Wavelet Kalman algorithm; filter*

1. Introduction

Electrical capacitance tomography technology (ECT, Electrical Capacitance Tomography) is developed in the mid eighties of the 20th century's application in multi phase flow parameter measurement of a process tomography technique (PT, Process Tomography) [1]. The principle is to rely on a set of electrode plates around the measured area to monitor the capacitance change caused by regional material concentration distribution changes , in order to determine the concentration of the substance in internal distribution, due to its non intrusive, fast response, low cost and other advantages, it can provide two-dimensional or three-dimensional visualization of the internal flow of the closed vessel and pipeline and has been rapid development in recent years [2]. ECT technology has been applied in many fields, including the measurement of gas-liquid two-phase flow void fraction measurement and flow pattern identification, visualization of fluidized bed gas-solid two-phase concentration distribution, pneumatic conveying, flame visualization, visualization of moisture migration process in frozen soil, *etc* [3]. ECT technology is mainly used in the parameter detection of multiphase flow, such as monitoring multiphase flow process, realization of the flow pattern identification and calculation of the phase holdup and other [4]. In multiphase flow system, the flow characteristics of the fluid in the pipeline are very fast, so the electrical capacitance tomography system must collect the data and process the data quickly [5]. Electrical capacitance tomography system mainly consists of three parts, namely capacitance array sensor, data acquisition system and image reconstruction system [6]. The array type capacitance sensor is composed of multi-pairs of capacitor plates which are evenly distributed around the pipe and can detect the transformation of the dielectric constant of the medium in the pipeline, data acquisition system is to collect and process the data,

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image reconstruction system is to solve the problem of image distortion caused by the "soft field" characteristics of capacitance sensor and Micro capacitance measurement noise and other factors. Data collection is the most important intermediate link, while filter plays an important role in the ECT data acquisition system. Its quality directly determines the accuracy and speed of collecting data of ECT data acquisition system [7].

Based on the wavelet Kalman algorithm, a new method for the realization of the filter using multiplexing and folding structure is proposed. The multi wavelet decomposition and reconstruction are combined into a filter module to improve the processing speed. As the calculation amount the high-pass filter and low-pass filter complete is same, in order to further enhance the speed, so that the high-pass filter and low-pass filter are calculated simultaneously to achieve parallel processing. It is simulated and verified in ISE environment. The experimental data shows that based on FPGA and wavelet Kalman algorithm, the filter realized by using of multiplexing and folding principle improves the speed of filtering, so that the ECT data acquisition speed can be improved, and it meets the requirements of real time processing of ECT data acquisition, provides a new method to realize the filter for ECT data acquisition system.

2. Working Principle of ECT Data Acquisition System

The overall structure of the ECT data acquisition system is shown in Figure 1. At present, the working principle of ECT data acquisition system is to take FPGA as the core control unit, FPGA issues a directive to DDS signal generator, then the DDS signal generator generates a sine or cosine AC excitation voltage $V_i(t) = A\sin(\omega t)$ or $V_i(t) = A\cos(\omega t)$, the generated voltage signal is loaded onto the excitation electrode, at the same time, capacitance value between the detected electrodes is transferred to the C/V conversion circuit , converted into a voltage value, namely, $V_0(t) = (C_x / C_f)A\sin(\omega t)$ or $V_0(t) = (C_x / C_f)A\cos(\omega t)$ and then data are sent into the A / D conversion circuit to digitize, after that, filtering and demodulating process is completed in FPGA to filter out the high frequency components which is not needed. After the completion of the demodulation and filtering, the processed data are sent into the memory, and transmitted to the computer for image reconstruction through the USB interface [8].

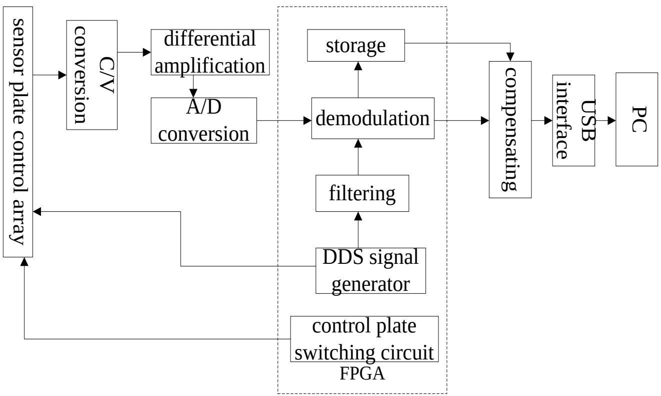

Figure 1. ECT Data Acquisition System

3. ECT Data Acquisition System Filter

3.1. Wavelet Kalman Algorithm

The specific flow of wavelet Kalman algorithm is shown in Figure 2. The concrete steps of the algorithm are to make the data collected by ECT data acquisition system preprocessed by multi wavelet to achieve preliminary denoising, threshold processing uses hard threshold function, then estimate the noise variance Q(t) and R(t) by noise statistical estimator, after that ,send the preprocessed data into the Kalman filtering module for filtering. If the filtering process has been completed, the data output, otherwise, the process is repeated until the whole iterative process ends.

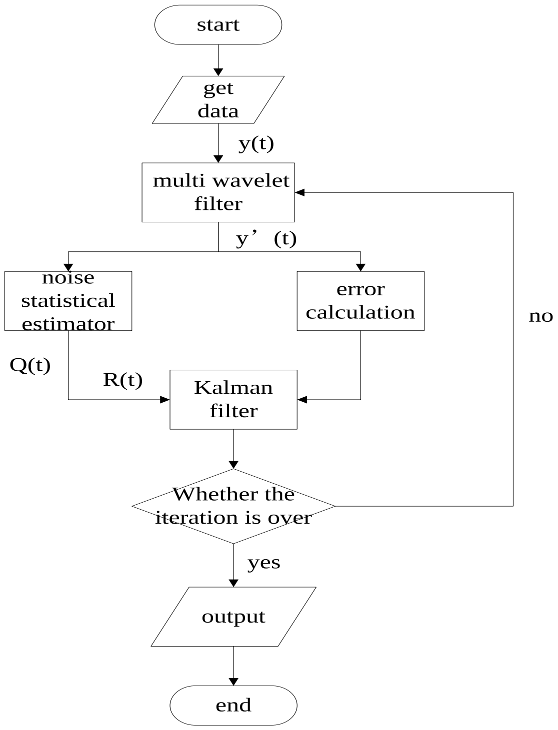

Figure 2. Flow of Wavelet Kalman Algorithm

3.2. Realization of Algorithm

Wavelet Kalman algorithm is divided into: pre filter, multi wavelet decomposition, coefficient threshold processing, multi wavelet reconstruction, post filter, Kalman filtering. If the algorithm is realized in accordance with the order, and caches all intermediate data, the overall structure of algorithm implementation is shown in Figure 3. When multi wavelet decomposition starts, firstly, the first layer decomposition of multi wavelet is carried out and gets the multi wavelet coefficients including the detail and average part , the detail part is sent into the coefficient processing module for threshold processing, then saved to the detail cache, and the average part is put into C1 cache, the second layer decomposition of multi wavelet continues until the decomposition process ends , and the process is the same as the first decomposition. The next is reconstruction of multi wavelet. The average part in Cn cache and the detail part in detail cache are placed into multi wavelet reconstruction module and get Cn-1, the process is repeated until the end, and then the data are put into post filter module for post filter processing

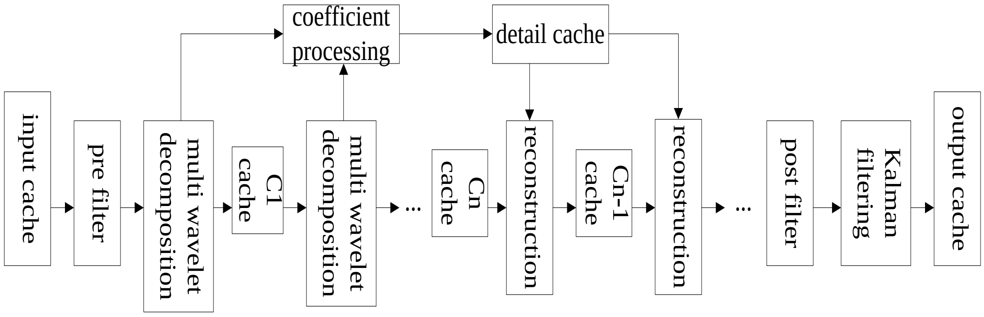

Figure 3. Implementation of Algorithm

The structure of Figure 3 shows that if the layers of multi wavelet decomposition are J, the data length is L, the word length of processing data and intermediate data is K, when the wavelet decomposition, filtering and reconstruction are carried out according to the tree structure, at least 2J filters and 2JLK bit storage units for intermediate data storage are required.

Therefore, when the number of wavelet decomposition is more, the more the number of wavelet decomposition and reconstruction module, the more the need of the storage unit, the greater the storage space, the slower the speed. The implementation method not only takes up large hardware resources, but also slows the filter speed, so it is necessary to improve the structure and design a reasonable implementation plan, so as to speed up the filtering speed.

4. Improved Filter of ECT Data Acquisition System

4.1. Integral Structure of Improved Filter

In order to accelerate the speed of operation, it is mainly that this link which is the multi wavelet decomposition to multi wavelet reconstruction is improved. To reduce the number of multi wavelet decomposition module and multi wavelet reconstruction module, reuse is the most simple and effective way, due to the multi wavelet decomposition and reconstruction can be written in a convolution form. Therefore, it can be a merger of the two into a module. The new filter is divided into: input and output module, memory module, multi wavelet filter module, Kalman filter module, control module. The multi wavelet filter module is divided into pre filter module, filter module, coefficient processing module and post filter module. The improved filter is shown in figure 4.

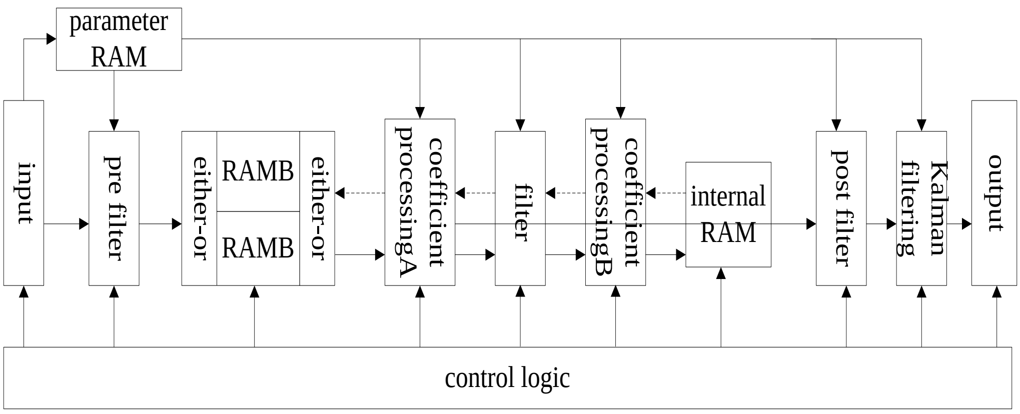

Figure 4. Overall Structure of Improved Filter

The working process of the improved filter is to make the initialized data store in the parameter RAM, and start the process of data filtering; the data are converted into matrix form by pre filtering processing, and then stored in the memory for multi wavelet decomposition. The process of multi wavelet decomposition is to make coefficient processing module A from RAMA or RAMB read data and transfer to filter module for multi wavelet decomposition. After the first layer decomposition, the data are entered into the coefficient processing module B by the filter module to complete down-sampling and threshold processing for the details of the multi wavelet coefficients. Finally coefficient processing module B writes data to the internal RAM, so the first layer decomposition and coefficient of threshold processing are completed. The Second layers of decomposition, as shown in the dotted line. Coefficient processing module B reads the average part of the multi wavelet coefficients of the first layer decomposition in the internal RAM, and sends them into the filter module to complete the second multi wavelet decomposition. The multi wavelet coefficients decomposed are went into Coefficient processing module A to complete down-sampling and threshold processing for the details of the multi wavelet coefficients, and then written to the RAMA or RAMB, the second layer decomposition and coefficient of threshold processing are completed. The third layer decomposition process is similar to the first one, and the fourth layer decomposition is similar to the second layer. The next is multi wavelet reconstruction, the process is that layers of multi wavelet decomposition are 4, the data from RAMA or RAMB are sent into Coefficient processing module A to complete up-sampling, then input onto the filter module for processing, the data are written to internal RAM after completing addition operation in the coefficient processing module B, the first layer reconstruction is completed. The second layer reconstruction begins, coefficient of processing module B reads data from internal RAM to complete up-sampling, then input them onto the filter module to for operation, the data are written to RAMA or RAMB after adding after completing addition operation in the coefficient processing module A, the second layer reconstruction is completed. Third layer reconstruction process is similar to that of the first layer, and the fourth layer is similar to the second layer.

When the multi wavelet reconstruction is done, the data are transmitted to the post filter module for filtering by coefficient processing module A.

4.2. Multi Wavelet Filter Module

Multi wavelet filter module mainly completes the pre filter, multi wavelet decomposition, threshold processing, multi wavelet reconstruction and post filtering. The multi wavelet decomposition and reconstruction are essentially convolution operation, so multi wavelet filter module is divided into the pre filtering, filter module, the coefficient processing module, the post filtering.

4.2.1. Filter Module

A core part of the filter is a filter module, and it is a key to data processing speed of the filter. Because the link which is multi wavelet filtering is to process matrix data, so matrix multiplier is used. PE is the basic unit to constitute a matrix multiplier, each PE includes a multiply add unit and a storage unit storing the result of the calculation. PE unit structure is shown in Figure 5.

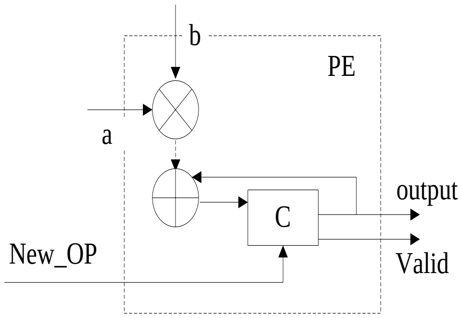

Figure 5. PE Cell Structure

Each PE unit, in addition to itself contains a storage unit that stores the intermediate results, has a storage unit that stores the final results in the matrix multiplier. In this way, the result of the multiplication calculation can be read by the processor, in the same time, the matrix multiplier can be carried out the next multiplication calculation, which improves the computation efficiency of the multiplier. Due to the relative independence of each PE unit in the design of the parallel matrix multiplier, the parallel computation of multi chip FPGA can be extended easily. When the computational performance of the system needs to improve, it can be achieved by increasing the number of matrix multiplier.

Because the high-pass filter and low-pass filter are equal to the computation, they are considered to be parallel processing, which can shorten the operation time and improve the speed of operation. As shown in Figure 6, filter based on dual multipliers for each multiplier is equipped with a pre processing module. Preprocessing module is mainly to read the matrix data involved in the operation, when a column or a row of the matrix data involved in the operation is zero, skip the calculation, not all zero, the read data are sent into the calculation in the queue, then operate next a column or a row of data, so as to avoid the unnecessary operation and improve the running speed. Number of PE units in Figure 6 depends on number of rows in the input data or number of columns of high pass and low pass filter. Each PE cell are independent, parallel computing, it is easy to add and delete PE unit, or extends to multiple FPGA, in addition, multipliers configure a storage unit for each PE to store the final result, the reading result and the calculating data can be simultaneously carried out, thereby it improves the efficiency.

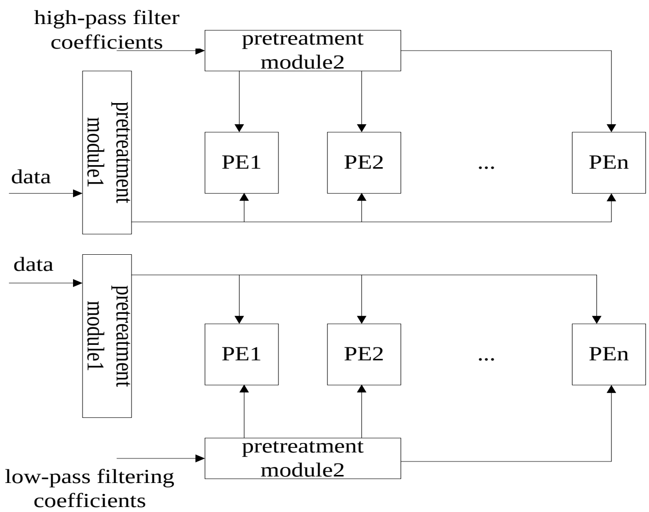

Figure 6. Filter Based On Double Multiplier

4.2.2. Coefficient Processing Module

Coefficient processing module is mainly to complete down-sampling of the multi wavelet coefficients after multi wavelet decomposition, at the same time, make the detail part of the multi wavelet coefficient perform threshold processing. When the reconstruction is carried out, coefficient processing module completes up-sampling of the multi wavelet coefficients and process.

There are a variety of methods for calculating the threshold, if the hardware computing method is used, it not only needs to estimate the noise, but also opens the root operation, while the method is relatively complex and of little significance. Therefore, the threshold got by the software or a priori knowledge is written into parameter storage unit by the input module, and it is read directly from the parameter storage unit, when needed.

Considering the filtering effect of the threshold function and the complexity of hardware implementation, the hard threshold function is used to threshold processing, and the threshold value is stored in the parameter storage unit directly by the input module. The realization of the hard threshold function is shown in Figure 7.

Hard threshold function:

$$\hat{W}_{j,k} = \begin{cases} W_{j,k} & |W_{j,k}| \geq \lambda \\ 0 & |W_{j,k}| < \lambda \end{cases} \tag{1}$$

In the formula: $W_{j,k}$ is the multi wavelet coefficient, and λ is the threshold value.

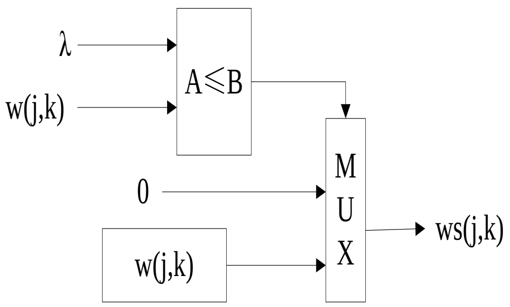

Figure 7. Hard Threshold Function

The ISE software is used to simulate the coefficient processing module. As shown in Figure 8, it is the function simulation result of the coefficient processing module (part).

From the point of view of the results of the function simulation, the written program is correct. When the multi wavelet decomposition is used, the multi wavelet coefficients are sampled, at the same time, threshold value is read from the parameter storage unit, and it is to complete threshold processing for the details of the multi wavelet coefficient by hard threshold function. Compared with that the threshold value is calculated by the hardware, or the hard threshold function is realized by software, it reduces the hardware resource and saves the processing time.

Figure 8. Function Simulation

5. Comparison of Experimental Results

We use the principle of folding structure and reuse to improve the filter which makes the algorithm realize step by step, to combine the multi wavelet decomposition and reconstruction into a filter module, simultaneously, and to realize the parallel processing of the high-pass filter as well as low-pass filter. After the improvement, the hardware resources which layer by layer decomposition, reconstruction and storage need are saved, and the processing speed is improved.

Experiments were carried out to test the original filter and the improved filter. The layers of multi wavelet decomposition are 4, and the hard threshold function is used to threshold processing. Compared to the time this part which is from the wavelet decomposition of the filter to the multi wavelet reconstruction spends, as well as the whole operation period of the filter, in order to compare the processing speed.

The original filter is used to test. The collected data are sent into the filter and the processes such as shown in Figure 3. According to the test, the multi wavelet decomposition to the end of the reconstruction needs 11.79 microseconds, the whole filtering process needs 20.28 microseconds.

Test of improved filter, as shown in Figure 4, the time required for this process which is from the coefficient processing module A to obtain data to the end of multi wavelet reconstruction--data is fed into the filter module is 4.341 microseconds, and the whole filtering process takes 12.83 microseconds.

Table 1 is the comparison of the time required for processing the data of the two kinds of filters, respectively, to compare the time required for the completion of the whole filtering process and the process from the multi wavelet decomposition to the end of the multi wavelet reconstruction.

Table 1. Data Processing Time Comparison

	Multi wavelet decomposition-reconstruction μs	Operation period μs
Original filter	11.79	20.28
Improved filter	4.341	12.83

The experimental data from table 1 are compared and analyzed. The improved type filter is compared with the original filter, and the speed of data processing is improved. It is mainly that because the link of multi wavelet decomposition and reconstruction saves a lot of time, so as to reduce the time the whole process spends.

Then we test the accuracy of the data which are processed by two kinds of filter, and use the mean square error and signal-to-noise ratio as the evaluation criterion. 10 sets of data were tested.

Variance is defined as:

$$\text{MSE}=\frac{1}{N}\sum_{i=0}^{N-1}(F_i - f_i)^2 \tag{2}$$

Among them, F_i is the original data, f_j is data after filtering, the smaller the variance, the more stable the data.

Signal-to-noise ratio is defined as:

$$\text{SNR}=10\lg\left[\frac{\sum_{n=0}^{N-1} S^2(n)}{\sum_{n=0}^{N-1}[S(n)-\bar{S}(n)]^2}\right] \tag{3}$$

In the formula, S(n) is the effective power of the original signal, $\overline{s}$(n) is the effective power of the signal after filtering. The higher the SNR, the less noise.

Table 2 is the variance and signal-to-noise ratio of the filter implemented step by step.

Table 2. MSE and SNR of the Original Filter

sequence	MSE	SNR
1	0.0060	70.3493
2	0.0048	71.3184
3	0.0040	72.1102
4	0.0049	71.2288
5	0.0043	71.7961
6	0.0039	72.2202
7	0.0034	72.8160
8	0.0045	71.5987
9	0.0057	70.5721
10	0.0059	70.4223

Table 3 Is The Variance And Signal-To-Noise Ratio Of Data Processing For Improved Filter.

Table 3. MSE and SNR of Improved Filter

sequence	MSE	SNR
1	0.0020	75.1205
2	0.0018	75.5781
3	0.0010	78.1301
4	0.0019	75.3433
5	0.0013	76.9914
6	0.0019	75.3433
7	0.0014	76.6695
8	0.0015	76.3699
9	0.0017	75.8263
10	0.0019	75.3433

Data in table 2 and table 3 show that the variance of data processing of improved filter is smaller than one of filter of the gradual implementation, and signal-to-noise ratio of the improved filter is bigger than one of the original filter because of the adoption of the principle of multiplexing and folding structure. So the data collected by ECT data acquisition system are more accurate and more stable, and it improves the accuracy of data acquisition of ECT data acquisition system.

6. Concluding Remarks

In ECT data acquisition system, the traditional method of realizing filter cannot guarantee the real-time data acquisition, because step by step implementation of multi wavelet decomposition and reconstruction limits the speed of data processing, thereby it reduces the speed of ECT data acquisition system to collect the data. Simulation experiments found that the filter using folded structure and multiplexing principle saves hardware resources and improves the precision of the processing speed and data acquisition, due to use a filter module to realize the multi wavelet decomposition as well as reconstruction, and make high pass filter and low-pass filter process the data at the same time. It provides a new method of filter realization for ECT data acquisition system

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