DSP Implementation of Neutron Radiation Detection Based on Kalman Filter

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Abstract: Aiming at the situation of nuclear neutron pulse count distortion and low measurement accuracy, a digital processing chip and Kalman filter are designed to replace the traditional hardware filtering method. The system uses TMS320F28335 as the main control chip, and takes advantage of the DSP-specific digital signal processing chip. After using the extended Kalman filter to reduce the noise and filter the pulse neutron count, the experiment proves that the nuclear pulse neutron count measurement after the extended Kalman filter process is stable, and the measurement accuracy has been significantly improved. The overall structure and working principle of the system are introduced, and specific hardware and software design schemes are given.

1. Introduction
The neutron radiation pulse energy spectrum measurement system is a professional equipment specially used to acquire and process nuclear neutron information. Traditional analog neutron radiation measurement instruments use multi-channel pulse amplitude analysis technology as the core to collect the amplitude of the analog nuclear pulse neutron radiation energy spectrum signal, but the hardware of traditional and pulsed neutron energy spectrum measurement systems mostly uses analog circuits, and the whole circuit architecture is complex and affects the system performance to some extent before each other. The traditional nuclear pulse neutron radiation energy spectrum measurement system can no longer meet the recognition and collection of high frequency pulse neutron counting.

2. Design of neutron radiation detection system
The neutron radiation pulse data readout system is mainly composed of hardware and software. The hardware part mainly includes two main modules: neutron radiation pulse data acquisition module and data processing module. The neutron radiation pulse data acquisition module mainly includes BGO neutron detector, photomultiplier tube, signal pre-processing and amplification circuit. The core neutron data processing module is mainly composed of a digital-to-analog conversion circuit with AD9226 as the core and a main control circuit with DSP28335 as the core.

The nuclear neutron pulse detected by the BGO neutron detector passes through the photomultiplier tube to establish a weak electrical pulse signal, and then passes through the signal preprocessing circuit to stabilize the pulse signal, and then through the amplification circuit to amplify the 5mV nuclear neutron pulse signal into energy 5V signal received by the ADC chip. The signal is converted into a
digital signal by AD9226 and then sent to DSP28335 after processing and then sent to the host computer for display.

![Diagram of neutron radiation detection system](image1)

**Figure 1. Block diagram of a neutron radiation detection system**

As shown in Figure 2, the output signal of the photodetector passes through C2, and the pulse signal is input from the inverting end of the operational amplifier. The signal is amplified by the charge sensitive amplifier and outputs a relatively stable voltage signal.

For the characteristics of short detector output signal period and small amplitude, the charge amplifier has high input impedance, large open-loop gain, good output stability, wide bandwidth and fast response, which can meet the requirements.

![Signal preprocessing circuit](image2)

**Figure 2. Signal preprocessing circuit**

In the charge sensitive amplifier, the input resistance is not $\infty$, and the output voltage signal is exponentially attenuated. However, after the pulse signal passes through the pre-amplifier circuit and the filtering process, the output voltage signal is generally bipolar and has some undershoot. The presence of undershoot will seriously affect the system's amplification performance for normal signals. In order to avoid the impact of negative kickback, it is not easy to use a high-pass circuit to differentiate the output signal of the charge sensitive amplifier. A zero-polarity cancellation circuit is needed to ensure that the differentiated output signal is a unipolar signal. Its principle is to cancel the level (zero) point of the transfer function of the previous stage and the zero (pole) point of the subsequent stage in a system with several stages in series. In terms of signal shaping, the time constant of the exponentially decay signal can be changed to improve the resolution.

As shown in Figure 3, for BOG neutron detector output signal, there is a serious tailing phenomenon. The differential signal can accelerate the drop, thereby eliminating the accumulation effect, but the sharpened signal tip is not conducive to peak detection and counting, so after passing the integration circuit, the tip can become smooth. At the same time, CR-RC circuit can filter and reduce noise in addition to pulse shaping.
As shown in Figure 4, Based on DSP+FPGA neutron radiation detection system, in order to improve the defects such as low control accuracy and system instability due to insufficient resources of the single chip microcomputer, and fully consider the characteristics of high control accuracy and large data collection of the entire system. Therefore, the dual-core system design is adopted. For the full use of resources, the DSP28335 and FPGA are divided, and the host computer display and communication parts are handed over to the DSP28335. The advantages of the DSP28335 in high performance and high precision are fully utilized. The data acquisition part of the BGO detector is handed over to the FPGA for processing. At the same time, DSP and FPGA can also communicate with each other to exchange and transfer resource data.

3. Research on EKF algorithm

Traditional linear Kalman filtering can make the best estimate of neutron radiation pulse data under the condition of Gaussian model.

\[
x_k = A x_{k-1} + B u_{k-1} + w_{k-1} \\
z_k = C x_k + v_k
\]

(1)

However, the traditional linear Kalman filter is biased towards parameter estimation, and does not care about the actual measured signal value, which may cause a large deviation in the final result. For this phenomenon, extended kalman filtering is introduced to solve the problem. The filtering algorithm estimates the predicted value and judges whether the parameter value of the system itself changes, so as to estimate and modify the model parameters and noise to improve the filter design and reduce the filter actual error.

Therefore, we introduce an extended Kalman filter model to optimize and correct the deviation of the neutron radiation pulse.

Step 1: Initialize the initial state X(0), Y(0), and covariance matrix P0.
Step 2: State prediction
\[ X(k | k - 1) - 0.5X(k - 1) + \frac{2.5X(k - 1)}{1 + X^2(k - 1)} + 8\cos(1.2k) \]  

Step 3: Observation and prediction

\[ P(k) = (I_n - K(k)H(k))P(k | k - 1) \]

Step 4: First-order linearized state equation, solving state transition matrix

\[ \phi(k) = \frac{\partial f}{\partial X} = 0.5 + \frac{2.5[1 - X^2(k | k - 1)]}{[1 + X^2(k | k - 1)]} \]

Step 5: First-order linearized observation equation to solve the observation matrix

\[ H(k) = \frac{\partial h}{\partial X} = \frac{X(k | k - 1)}{10} \]

\[ H(k) = \frac{dy}{dx} \]

Step 6: Seeking covariance matrix prediction \( P(k | k - 1) \).

\[ P(k | k - 1) = \phi(k)P(k - 1 | k - 1)\phi^T(k) + Q \]

Step 7: Find the Kalman filter gain

\[ K(k) = X(k | k - 1)H^T(k)(H(k)P(k | k - 1)H^T(k) + R)^{-1} \]

Step 8: Seeking status update

\[ X(k) = X(k | k - 1) + K(Y(k) - Y(k | k - 1)) \]

Step 9: Covariance update

\[ P(k) = (I_n - K(k)H(k))P(k | k - 1) \]

Figure 5. EKF flow chart
The software design of the DSP-based neutron radiation pulse data readout system mainly realizes the real-time acquisition of neutron radiation pulses by the neutron detector, as well as the AD9226 sampling timing control, including data storage and display of nuclear neutron pulses.

4. Experimental results and analysis
First, through analysis, we can know that the neutron radiation pulse signal is a single model, and the extended kalman-simulink mathematical model is established for the neutron radiation signal according to the extended kalman filtering algorithm. Measurement noise $R=1$, sampling time is set to 1.

Then output a 50ns Gaussian pulse through the signal generator, through the acquisition, pre-processing, amplification, digital-to-analog conversion modeling of the neutron radiation analog signal, read the cache data in the FPGA through the EMIF interface of the DSP, and expand the signal Kalman filter algorithm processing, and finally get the neutron radiation signal read data.

It can be seen from Figure 6 that the system error has been kept below 1%, which meets the error index of 2% of the initial design of the system, but the error is relatively large in the later period. Therefore, in actual measurement, we should further optimize the data collection device of the detector and optimize the noise interference in the later period, and further need to correct the parameters according to the detection distance to reduce errors and improve accuracy.

5. Conclusion
This paper proposes a DSP implementation method based on the extended Kalman filter nuclear pulse neutron readout system. This method introduces the extended Kalman filter method based on the powerful digital signal DSP processing capability, which overcomes the signal-to-noise distortion and system error caused by traditional hardware direct reading and filtering.
The experimental results show that the neutron radiation pulse after Kalman filtering greatly improves the measurement accuracy and realizes high-precision nuclear pulse neutron count recognition.

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