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Principal Component Analysis for pulse-shape discrimination of scintillation radiation detectors

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ABSTRACT

In this paper, we report on the application of Principal Component analysis (PCA) for pulse-shape discrimination (PSD) of scintillation radiation detectors. The details of the method are described and the performance of the method is experimentally examined by discriminating between neutrons and gamma-rays with a liquid scintillation detector in a mixed radiation field. The performance of the method is also compared against that of the conventional charge-comparison method, demonstrating the superior performance of the method particularly at low light output range. PCA analysis has the important advantage of automatic extraction of the pulse-shape characteristics which makes the PSD method directly applicable to various scintillation detectors without the need for the adjustment of a PSD parameter.

1. Introduction

In several scintillation detectors sensing differences in the shape of output pulses provide very useful information on the type of radiation interacting with the detector. This is commonly referred to as pulse-shape discrimination (PSD). The most common PSD application is in the discrimination between neutrons and gamma-rays with organic scintillation detectors used as fast neutron detector [1]. The PSD techniques are also widely used in applications involving phoswich scintillation detectors [2]. The traditional PSD methods are the Charge-Comparison (*CC*) and the Zero-crossing (*ZC*) methods which have been implemented on analog circuitry for several decades [3,4]. The *CC* method is based on the comparison of integrals of the pulses for two different time intervals while in the *ZC* method a zero-crossing time bears the pulse-shape information. In recent years, there has been tremendous interest in using digital pulse-processing methods for PSD of scintillation detectors and a number of techniques such as digital versions of *CC* and *ZC* methods have been used for this purpose [5,6]. Moreover, pure digital techniques based on curve fitting [7], frequency domain analysis [8] and neural networks [9] have been used for PSD applications. Furthermore, digital PSD systems with the capability of real-time operation have been developed [10]. However, the available PSD methods are either computationally time intensive or require a PSD parameter to be precisely adjusted in accordance to the pulse-shape characteristics of the detector concerned. In this paper, a new digital PSD method based on the Principal Component Analysis (PCA) of sampled detector pulses is proposed. PCA is a widely used technique for extracting strong patterns in a dataset and has found applications in various disciplines such as image processing, neuroscience, etc. [11]. Our motivation for employing PCA for PSD applications is that PCA analysis is inherently adaptive to the intrinsic statistical characteristics of the data, and therefore, a PCA-based PSD system would be directly applicable to various scintillation detectors without the need for adjusting a PSD parameter. We describe the details of the method and the performance of the method is experimentally examined by discriminating between neutrons and gamma-rays with a liquid scintillation detector in a mixed radiation field. The performance of the PCA pulse classification algorithm is also compared against that of the conventional *CC* method.

2. The PCA method

In most of the scintillation detectors, a PSD technique makes use of a simple basic fact that the decay-times of a scintillation light pulse are dependent on the type of radiation interacting with the detector. The shape of the pulses is, however, subject to variations due to statistical fluctuations in the number of photoelectrons, time spread in the photomultiplier tube (PMT) and electronic noise [12]. Our PSD method is based on the employment of a PCA analysis for extracting the patterns in the decay-times of sampled PMT pulses, thereby different types of radiation can be identified. A comprehensive review of PCA can be found in many

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references (e.g. Ref. [11]). Here, we briefly describe the PCA procedure in regard to our PSD application. In computational terms, the PSD method is based on the extraction of the eigenvectors and eigenvalues of a data covariance matrix formed by a set of pulses acquired during a pre-acquisition run. Consider during a pre-acquisition run a set of n pulses are acquired. Each pulse is composed of m samples covering the whole duration of the pulse. The pulses are then normalized to their amplitude and a data matrix X is formed in such a way that each pulse represents a row of the matrix. The matrix $X_{n\times m}$ is described as:

$$X_{n\times m} = \begin{bmatrix} x_{1,1} & x_{1,2} & . & . & x_{1,m} \\ . & . & . & . & . \\ . & . & . & . & . \\ . & . & . & . & . \\ x_{n,1} & . & . & . & x_{n,m} \end{bmatrix} \quad (1)$$

The j-th column of this matrix represents samples of random variable x_j which are the normalized amplitudes of the pulses at a specific time during their lifetime. The covariance matrix of the random variables x_j will be a matrix $C_{m\times m}$ as:

$$C_{m\times m} = \begin{bmatrix} C_{1,1} & C_{1,2} & . & . & C_{1,m} \\ . & . & . & . & . \\ . & . & . & . & . \\ . & . & . & . & . \\ C_{m,1} & . & . & . & C_{m,m} \end{bmatrix}. \quad (2)$$

The elements of the covariance matrix $C_{m\times m}$ are computed by the following:

$$C_{j,k} = \sum_{i=1}^{n} \frac{(x_{i,j}-\overline{x}_j)(x_{i,k}-\overline{x}_k)}{n-1}, \quad (3)$$

where $\overline{x}_j$ and $\overline{x}_k$ are the average values of column j and k, respectively. By having the covariance matrix C, the eigenvalues and eigenvectors of the matrix can be easily computed. A nonzero vector q of dimension m is an eigenvector of the square matrix $C_{m\times m}$, if it satisfies the Eigen equation:

$$Cq = \lambda q, \quad (4)$$

where λ is a scaler called eigenvalue. Each eigenvalue corresponds to an eigenvector $q_{m\times 1}$. In practise, only the eigenvectors associated with the largest eigenvalues are used for PCA analysis. If we use the k eigenvectors corresponding to k largest eigenvalues $\lambda_1,\ldots\lambda_k$, then the PCA transformation reduces the dimension of an input pulse vector from m to k. By using the k eigenvectors, we can create the matrix $Q_{m\times k}$ as:

$$Q = [q_1 \quad q_2 \quad \cdots \quad q_k]. \quad (5)$$

The matrix Q is then used to extract the k principal components of an arbitrary input pulse. To do so, the input pulse is normalized to its amplitude and then the principal components of the normalized pulse $y_{1\times \mathrm{m}}$ are calculated as:

$$PC = yQ = \left[pc_1 \quad pc_2 \quad \ldots \quad pc_k\right] \quad (6)$$

The projected vector PC is now of dimension k and its elements are termed the first principal component (pc_1), the second principal component (pc_2) and so on. In fact, the principal components are a set of uncorrelated variables that reflect most of the statistical variations in the shape of the input pulses. In our study, the principal components of input pulses are examined as a PSD index which determines the type of radiation.

3. Experimental setup

In our experiments, a cylindrical NE213 liquid scintillation detector (2″ × 2″) coupled to a PMT of type R329 Hamamatsu was used. The detector container is made of aluminium and the PMT is directly mounted on the back circular surface of the detector. The detector has a 0.5 mm thick aluminium window. The PMT was operated with a negative voltage of 1600 V and the pulses from the anode of the PMT were directly digitized by using a fast waveform digitizer at 4 GS/s sampling rate and with 10-bit resolution (model DC252HF from Agilent Technologies Inc). Tests were carried out using an americium–beryllium (Am–Be) neutron source. A lead brick was placed in front of the detector to increase the ratio of the number of recorded neutrons to gamma-rays. Some tests with standard laboratory sources were also performed to characterise the light output performance of the system. The sampled PMT pulses were analyzed with algorithms written in MATLAB programming environment.

4. Experimental results

In the first step, we calibrate the light output of the system. The calibration was performed by integrating the sampled pulses and shaping the pulses with a CR–RC filter before measuring the amplitude of the pulses [13]. Prior to the integration process, the baseline of each pulse was corrected by subtracting the average of the samples before the trigger from all pulse samples. The shaping time constant of the filter was 0.5 μs. The Compton edges in the pulse-height spectrum of data taken by ^{137}Cs and ^{22}Na were used for the calibration [14], indicating that our system is able of accepting pulses of light outputs from 85 keVee to about 1000 keVee (electron equivalent energy). The eigenvectors were determined by using a data matrix containing 3000 pulses acquired during the pre-acquisition run. Each pulse in the matrix contains 700 samples and the pulses are aligned in time by the trigger level of the digitizer. It is worth mentioning that the number of pulses is sufficiently large to yield a good statistical accuracy. A large number of pulses complicates the calculation of eigenvectors by increasing the size of the initial data matrix while it has little effect of the statistical accuracy of the calculations. Fig. 1 shows a typical input pulse and the first eigenvector extracted from the data matrix. In our study, the first four eigenvectors were examined for the PSD purpose. The examination of the PSD performance of the eigenvectors was performed by using a separate set of pulses. Fig. 2 shows the scatter plots of the first and second components of pulses against the corresponding light outputs. It is seen that, by using the first principal component, the neutron and gamma-rays are distributed in two different regions

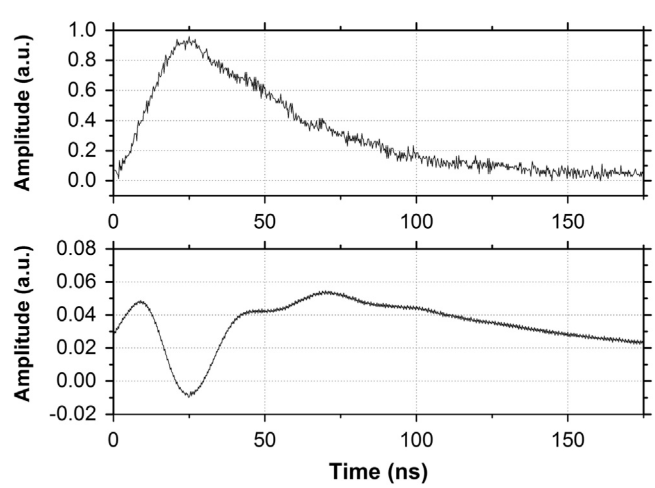

Fig. 1. (Top) A sample input pulse and (Bottom) the first eigenvector calculated by using pules acquired during the pre-acquisition run.

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