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A METHOD OF IDENTIFICATION OF RTS COMPONENTS IN NOISE SIGNALS

Noise signals containing two components with different distribution of current values of the noise signal, i.e. a component with Gaussian distribution and a component with non-Gaussian distribution, were analyzed. The non-Gaussian component was recognized as Random Telegraph Signal (RTS) noise. The method which enables RTS noise identification was presented. The results of an identification of RTS noise in inherent noise signals of type CNY17 optocoupler devices are included. The quality of the proposed method was verified on the base of histograms of two components of noise signal and on the base of the Noise Scattering Pattern (NSP) method.

Keywords: RTS noise, piece-wise constant approximation.

1. INTRODUCTION

With decreased dimensions of semiconductor devices, RTS signals are frequently observed in the device noise signals. Noise as a diagnostic tool for quality control and reliability estimation of semiconductor devices has been widely accepted and used and there are many papers published on this subject [1-4]. The parameter estimation of RTS noise impulses is also a way of localizing impurities in semiconductor materials [3, 5].

A number of methods of extracting RTS impulses are still developed [3, 6-9]. In this paper a new piece-wise constant approximation method is proposed.

The proposed computing procedure of identification of multi-level RTS noise which is being described here contains the following sub-procedures:

1. An algorithm of piece-wise constant approximation of the signal being analysed. This algorithm contains a threshold extraction procedure of the intervals in the domain of the signal and a mean-value approximation procedure of the signal in each of the extracted intervals.
2. The procedure which makes it possible to chose the proper threshold of extraction.
3. Quality estimation procedure of RTS noise extraction from a given noise signal.

Let $x(t)$ be the measured noise signal. A signal $x(t)$ is considered, by assumption, to be the sum $x(t) = s(t) + v(t)$, where $s(t)$ is assumed to be the RTS component of $x(t)$ and $v(t)$ is the remaining noise component of $x(t)$.

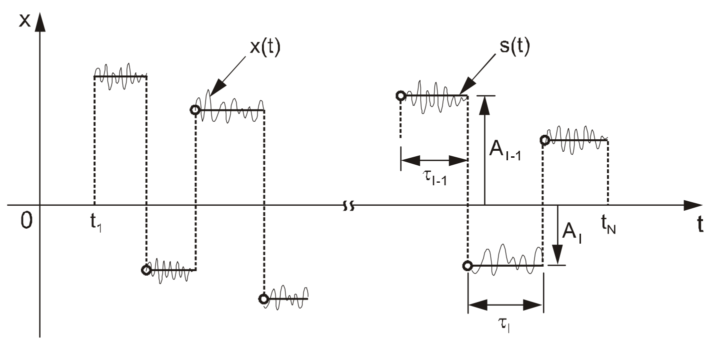


Fig.1. Noise signal $x(t)$ and the extracted RTS component $s(t)$.

Let $(x[n])_{n=1,2,\cdots,N}$ be a sequence of digital samples of the signal $x(t)$ measured at the momemts $t_1, t_2, \cdots, t_N$, N being the number of samples. Thus, $x[n] = x(t_n)$, for $n = 1, 2, \cdots, N$. A constant step Δt has been assumed for the sequence $t_1, t_2, \cdots, t_N$. That is, $t_{i+1} = t_i + \Delta t$, for $i = 1, 2, \cdots, N-1$.

To the decomposition $x(t) = s(t) + v(t)$ there corresponds the decomposition $x[n] = s[n] + v[n]$, which is defined for the sequence $(x[n])_{n=1,2,\cdots,N}$ of digital samples of the signal $x(t)$ being measured. The component $s[n]$ is considered to be the RTS component of $x[n]$, while $v[n]$ is the remaining noise component of $x[n]$.

It has been assumed that $v(t)$ is noise having a zero mean value, where the arithmetic mean value is calculated in each of the time intervals being the domain of the successive RTS impulse contained in $s(t)$. It has been assumed that this is also valid, with a sufficiently good precision, for the sequence $(x[n])_{n=1,2,\cdots,N}$ of digital samples of the signal $x(t)$ being measured. That is, one assumes that for a sufficiently large number of uniformly distributed digital samples of a measured signal $x(t)$, where the samples are contained in a finite time interval, there exists a decomposition $x[n] = s[n] + v[n]$ such that $s[n]$ is a discrete-time RTS, and the mean value of the remaining noise component $v[n]$ is equal to zero, with sufficiently good precision, in each of the discrete-time intervals being the domain of the successive RTS impulse in $s[n]$.

2. DESCRIPTION OF AN ALGORITHM OF PIECE-WISE CONSTANT APPROXIMATION OF A DISCRETE SIGNAL

The following definitions and notations are used. Let L denote the number of RTS impulses which are contained in the discrete-time signal $s[n]$ being the extracted RTS component of the discrete-time noise signal $x[n]$ obtained as the result of measurement of the noise signal $x(t)$ at discrete time values. Let W_l, $l \in \{1, 2, \cdots, L\}$, be the successive subsequence of the sequence $(x[n])_{n=1,2,\cdots,N}$ of digital samples of the noise signal $x(t)$ being measured, which corresponds to the entire discrete-time RTS impulse contained in the extracted RTS component $s[n]$ of $x[n]$. By m_l one denotes the number of digital samples, which are contained in W_l, $l \in \{1, 2, \cdots, L\}$. The number m_l, $l \in \{1, 2, \cdots, L\}$, is equal to the number of digital samples which are contained in the RTS impulse of number l of the RTS signal $s[n]$ extracted from $x[n]$. Thus, the impulse W_l, $l \in \{1, 2, \cdots, L\}$, is the following subsequence of $(x[n])_{n=1,2,\cdots,N}$,

$$W_l = (x[M_l + 1], x[M_l + 2], \cdots, x[M_l + m_l]), \tag{1}$$

where $M_l = 0$, for $l = 1$, and $M_l = m_1 + m_2 + \cdots + m_{l-1}$, for $2 \le l \le L$. The duration time τ_l of the impulse W_l is equal to $(m_l\text{-}1)\Delta t$, where it has been assumed that $t_{i+1} = t_i + \Delta t$, for each $i = 1, 2, \cdots, N-1$. To the RTS component of an RTS impulse W_l of number l corresponds the constant sequence $(A_l, \cdots, A_l)$, where the length of this sequence is equal to m_l and A_l is the level of the RTS impulse of number l.

There is a threshold value $\Delta x \geq 0$ in the computing procedure of extraction of the RTS component $s[n]$ of a noise signal $x[n]$. The extraction procedure of an RTS component $s[n]$ has been proposed to be a piece-wise constant threshold approximation algorithm of the analysed signal $x[n]$, where Δx is a given threshold value.

The algorithm of a piece-wise constant approximation of a discrete-time signal $x[n]$ (of a sequence of digital samples of a measured signal $x(t)$), which has been used in the computer processing of noise, is described in the following way. One sets $l = 1$ and $W_1[1] = x[1]$ at the begin. The successive element $x[k]$ of the sequence $(x[n])_{n=1,2,\cdots,N}$ is considered to be the successive element of the subsequence W_l being extracted at the actual step l if,

$$\left| x[k] - x[M_l + 1] \right| \leq \Delta x \,. \tag{2}$$

If condition (2) is not satisfied for the successive element $x[k]$ of $(x[n])_{n=1,2,\cdots,N}$ and for the first element $x[M_l + 1]$ of the subsequence W_l being extracted as a subsequence of the successive elements of $(x[n])_{n=1,2,\cdots,N}$, then $x[k]$ becomes the first element of the subsequent subsequence W_{l+1}.

The subsequent subsequences W_l, $l = 1, 2, \cdots, L(\Delta x)$, which have been extracted from the entire sequence $(x[n])_{n=1,2,\cdots,N}$, are being saved. The number L of subsequences depends on the threshold Δx. The approximate level $\widetilde{A}_l$ of the RTS impulse of number l, which is contained in the signal $x[n]$, is now defined to be the mean value of the respective sequence W_l. The elements of each of the subsequences $(v[k])_{k = M_l+1, M_l+2, \cdots, M_l+m_l}$, for $l = 1, 2, \cdots, L(\Delta x)$, are next defined to be the successive numbers $x[k] - \widetilde{A}_l$. It is also useful to define the sequence $(z[n])_{n=1,2,\cdots,N}$, whose successive elements are given by:

$$z[n] = \widetilde{A}_l \,, \tag{3}$$

for each $n \in \{M_l + 1, M_l + 2, \cdots, M_l + m_l\}$, where $l \in \{1, 2, \cdots, L(\Delta x)\}$.

There is given a sequence $(x[n])_{n=1,2,\cdots,N}$ of digital samples of a signal $x(t)$ and a threshold value Δx. The sequence $(x[n])_{n=1,2,\cdots,N}$ is assumed to be the sum of the discrete-time RTS $(s[n])_{n=1,2,\cdots,N}$ and the remaining component $(v[n])_{n=1,2,\cdots,N}$. That is, $x[n] = s[n] + v[n]$, for each $n = 1, 2, \cdots, N$. Let $\overline{L}$ denote the number of discrete-time RTS impulses in $(s[n])_{n=1,2,\cdots,N}$. It is assumed that the arithmetic mean value of each of the subsequences $(v[k])_{k = M_l+1, M_l+2, \cdots, M_l+m_l}$, $l = 1, 2, \cdots, \overline{L}$, of the sequence $(v[n])_{n=1,2,\cdots,N}$ is equal to zero. The notations used here have been introduced in the description of discrete-time RTSs.

Define the diameter

$$dia\, W_l = max\{\left| x' - x'' \right| : x',\ x'' \in W_l\} \,, \tag{4}$$

of each of the subsets W_l, $l = 1, 2, \cdots, \overline{L}$, and the distance

$$dist\,(W_p, W_{p+1}) = min\{\,|x' - x''| : x' \in W_p \text{ and } x'' \in W_{p+1}\}, \tag{5}$$

of the successive two subsets W_p and W_{p+1}, for each $p = 1, 2, \cdots, \overline{L} - 1$.

The following is valid: if

$$dia\, W_l \leq \Delta x, \text{ for each } l = 1, 2, \cdots, \overline{L} \tag{6}$$

and

$$dist\,(W_p, W_{p+1}) > \Delta x, \text{ for each } p = 1, 2, \cdots, \overline{L} - 1, \tag{7}$$

then the sequence extracted from the sequence $(x[n])_{n=1,2,\cdots,N}$ with the use of the described computing algorithm is equal to the sequence $(s[n])_{n=1,2,\cdots,N}$. There exists a threshold value Δx such that the inequalities (6) and (7) are satisfied for the sequence $(x[n])_{n=1,2,\cdots,N}$ which is under consideration, if

$$max\, dia\, W_l < min\, dist\,(W_p, W_{p+1}), \tag{8}$$

for $l = 1, 2, \cdots, \overline{L}$, and $p = 1, 2, \cdots, \overline{L} - 1$.

If relation (8) is satisfied by the sequence $(x[n])_{n=1,2,\cdots,N}$ being considered, then the number $L(\Delta x)$ depends on Δx as it has been shown in Fig. 2. L_o denotes the value of L at $\Delta x = 0$. Note that $L_o = N$ if, and only if, $x[n+1] \neq x[n]$, for $n = 1, 2, \cdots, N - 1$.

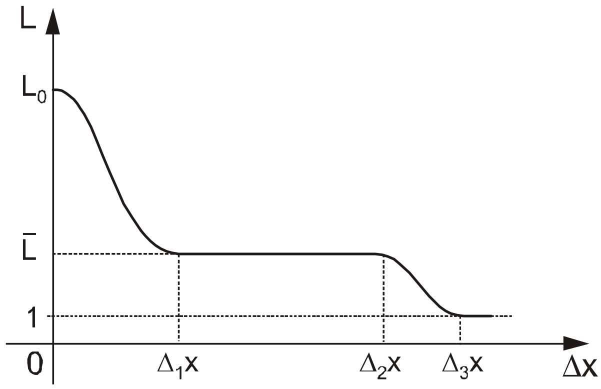


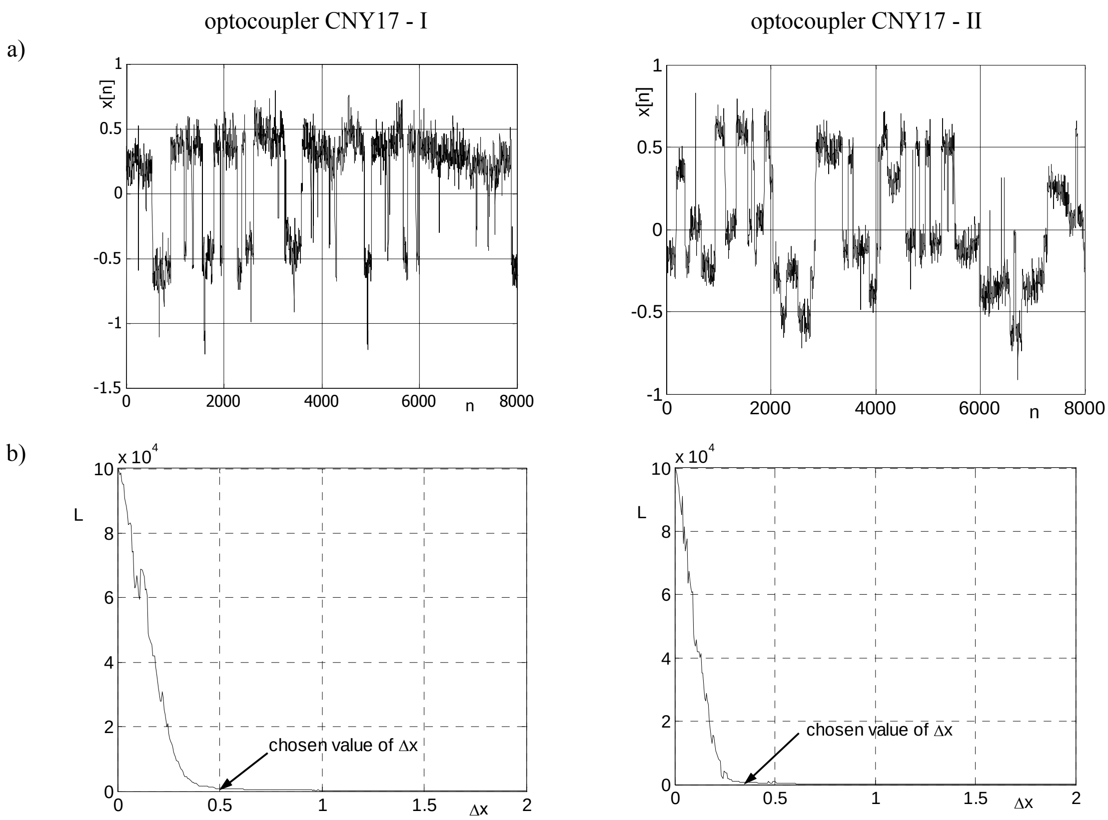
Fig. 2. Plot which illustrates the dependence of the number L of the extracted sequences W_l, $l = 1, 2, \cdots, L(\Delta x)$, on threshold Δx.

One obtains $L(\Delta x) = \overline{L}$, for $\Delta x \in [\Delta_1 x, \Delta_2 x]$, where the values $\Delta_1 x$ and $\Delta_2 x$ are marked in Fig. 2. Let $(z[n])_{n=1,2,\cdots,N}$ be the Eq. (3) of numbers which corresponds to the respective sequence $(W_j)_{j=1,2,\cdots,L(\Delta x)}$ extracted from the sequence $(x[n])_{n=1,2,\cdots,N}$ with use of the algorithm being described, for a threshold value equal to Δx. Assume that Eq. (8) is satisfied by the sequence $(x[n])_{n=1,2,\cdots,N}$. Then for $\Delta x \in [\Delta_1 x, \Delta_2 x]$, the obtained sequence $(z[n])_{n=1,2,\cdots,N}$ is equal to the component $(s[n])_{n=1,2,\cdots,N}$ of $(x[n])_{n=1,2,\cdots,N}$, and the extraction (the piece-wise constant approximation) algorithm yields the proper extraction result, which is also the desired result if $(x[n])_{n=1,2,\cdots,N}$ is the sequence of discrete samples of a noise signal $x(t)$. It is also to be noted that the curve in Fig. 2 is an approximation of the accurately-drawn curve for Δx in $(0, \Delta_1 x) \cup (\Delta_2 x, \Delta_3 x)$.

In conclusion one obtains that the algorithm, which has been described, of a piece-wise constant approximation of a sequence of numbers (of a sequence of digital samples) makes it possible to extract the RTS component of a discrete noise signal. If a discrete noise signal satisfies the Eq. (8) then one obtains the proper extraction result. If the Eq. (8) is not satisfied by the noise signal being analysed, one should verify the accuracy of the extraction result. This can be done by direct comparison of a given noise signal and the extracted RTS component, and by analysing the statistical properties of the remaining noise component which has been obtained in the result of subtraction of the extracted RTS component from the entire noise signal.

3. RESULTS OF EXPERIMENTS

The examples of plots, which show the dependence of the number L of extracted impulses on the threshold value Δx are drawn in Figs. 3b, 3c. The plots in Fig. 3 have been obtained for the sequences of 10^5 digital samples being the results of the measurement of noise (of the low frequency noise signals) in CNY17 optocouplers numbered by I and II.



c)

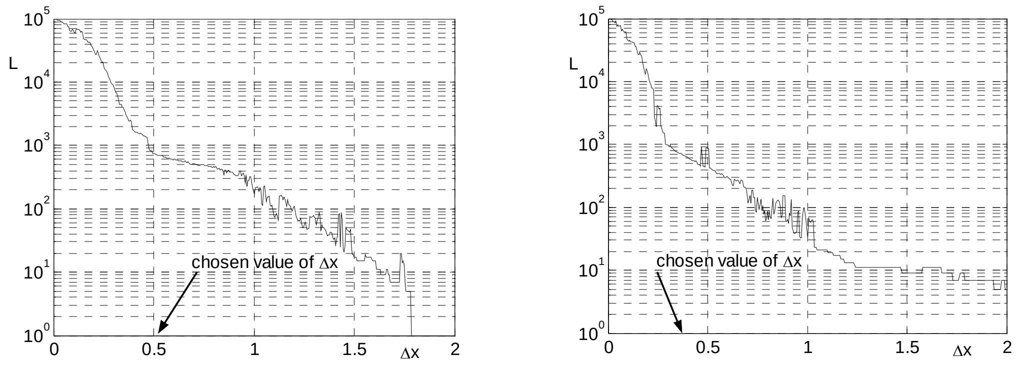


Fig. 3. The choice of proper threshold Δx values used in extraction algorithm of RTS signals of the optocouplers CNY17 – I and CNY17 – II: a) segments of the measured low-frequency noise signals, b) dependence $L = L(\Delta x)$ in the *lin-lin* scales , c) dependence $L = L(\Delta x)$ in the *lin-log* scales.

The plots in Fig. 2 and in Fig. 3b have the same shape. However, one should note that the relation $max\,dia\,W_l < min\,dist\,(W_p, W_{p+1})$, where $l \in \{1, 2, \cdots, L(\Delta x)\}$ and $p \in \{1, 2, \cdots, L(\Delta x) - 1\}$, may not be satisfied for any threshold value Δx by the respective sequence which has been extracted from the sequence of digital samples obtained as the result of measurement of the low frequency noise of a semiconductor device.

The best value $\widetilde{\Delta}_1 x$ of threshold Δx should be found and then it should be verified by numerical experiments for the sequence of digital samples which have been measured for a semiconductor device under consideration. It has been experimentally verified that the best value $\widetilde{\Delta}_1 x$ of threshold Δx should be chosen so as to be the point of Δx axis at which the absolute value of the derivative of the function $L = L(\Delta x)$ decreases visibly, at about one range of values, as Δx increases. In every case the dependence $L = L(\Delta x)$ should be obtained numerically, with the use of the described algorithm, for the sequence of digital samples of a noise signal. In order to assure a sufficiently accurate plot $L = L(\Delta x)$, the threshold value Δx was changed from $\Delta x = 0$ to $\Delta x = \Delta_3 x$ with the step equal to 0.005.

The threshold values, in the described algorithm, which assure the best possible extraction of RTS components from noise signals, where the noise signals have been measured in the optocouplers I and II, respectively, are marked on the Δx axes of the respective plots in Fig 3.

The accuracy of extractions has been verified by comparing the noise signals which have been measured, and the corresponding extracted RTSs, as shown in Fig. 4.

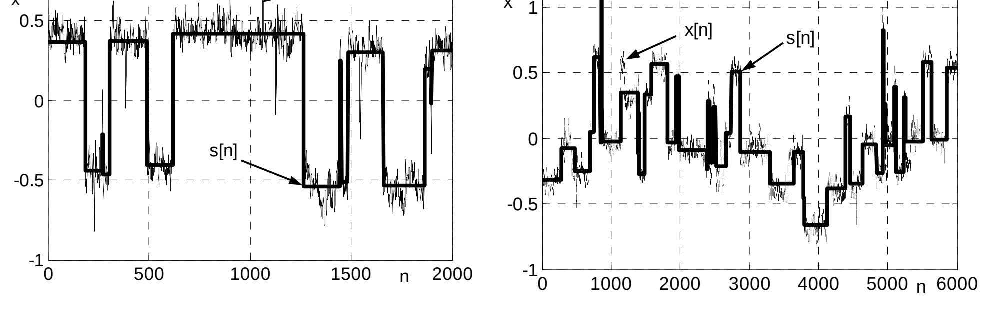


Fig. 4. Low-frequency noise signals which have been measured in the optocouplers CNY17 – I and CNY17 – II and the numerically extracted RTS components.

The accuracy of extractions has been also verified by analyzing the statistical properties of the remaining noise components, which are expected to be Gaussian noise signals having zero mean values, if sufficiently long intervals of observations had been taken into account.

In Figures 5a, 5b and 5c the histograms are plotted of values and NSPs (Noise Scattering Patterns method [1]) of the low frequency noise signal $x[n]$ which has been measured in the optocoupler CNY17 – I, and of the extracted RTS and the remaining components of the noise signal $x[n]$, where the extraction has been obtained with the use of the described identification algorithm.

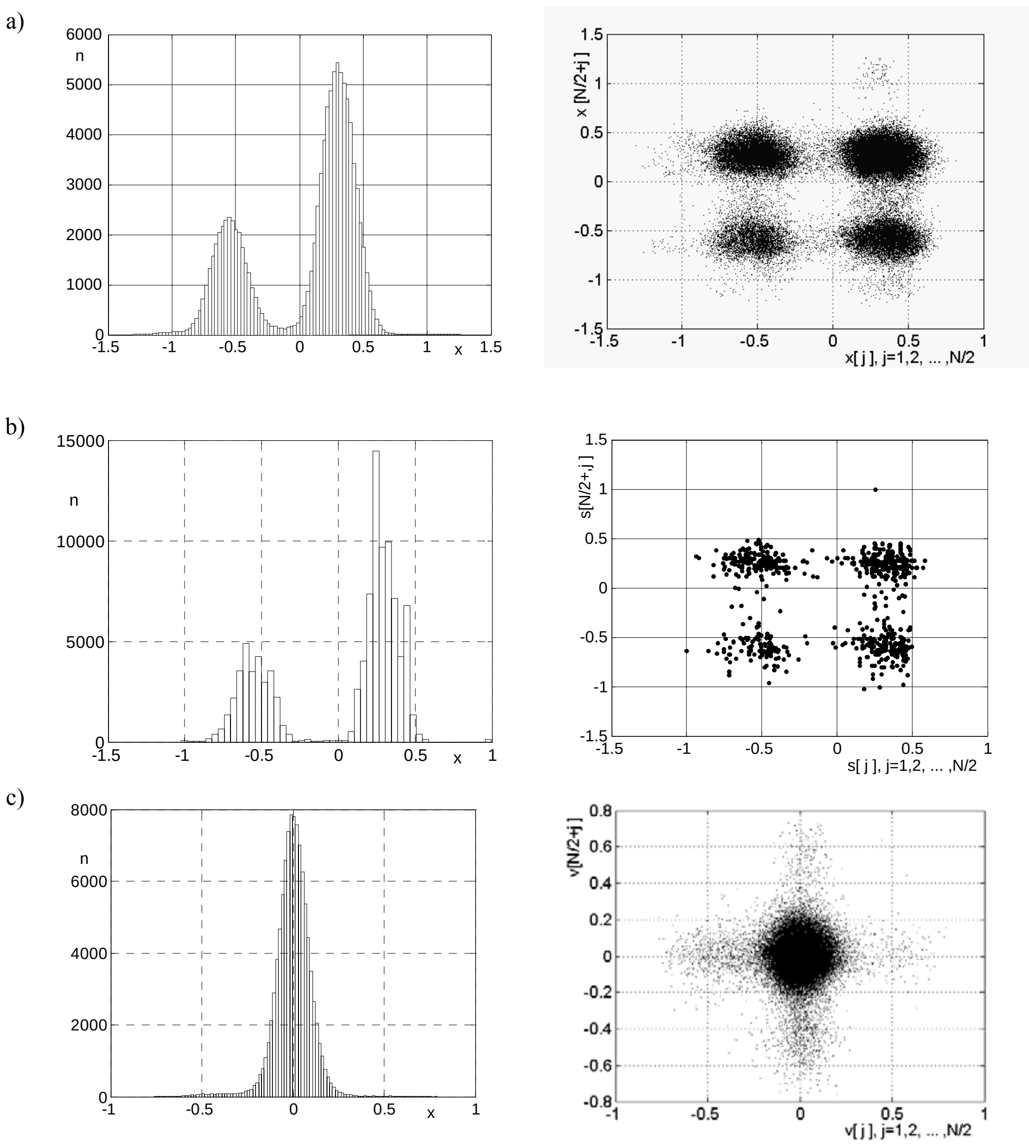


Fig. 5. Statistical properties of the low-frequency noise signal in the optocoupler CNY17 – I. Histogram of signal values and NSP plot which have been obtained: a) for the measured noise signal $x[n]$, b) for the extracted RTS component $s[n]$ of $x[n]$, and c). for the remaining component $v[n]$.

Figure 6 shows the histograms of the duration times of the up and down RTS impulses observed in the extracted RTS component of the low frequency noise signal measured in the optocoupler CNY17 numbered by I. The extraction of the RTS component has been performed with the use of the described identification algorithm.

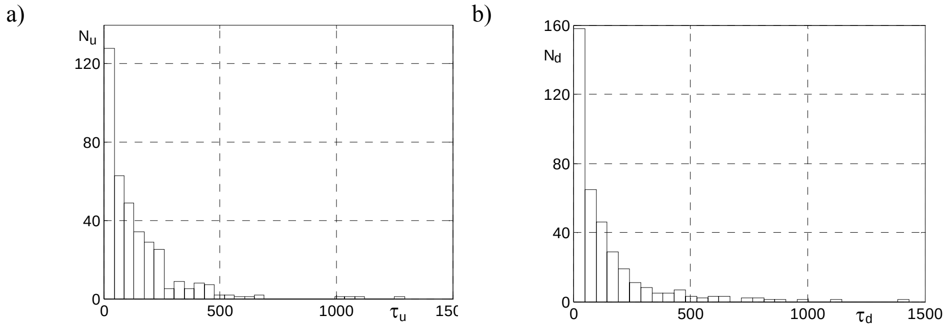


Fig. 6. Histograms of RTS impulses observed in the optocoupler CNY17 - I
a – number N_u of up impulses, b – number N_d of down impulses.

4. CONCLUSIONS

The algorithm describing a piece-wise constant approximation of a sequence of numbers (of a sequence of digital samples) makes it possible to extract the RTS component of a discrete noise signal. If the condition (8) is satisfied by a noise signal being analysed, then there exists an interval $[\Delta_1 x, \Delta_2 x]$ of the threshold Δx values such that for each $\Delta x \in [\Delta_1 x, \Delta_2 x]$ one obtains the proper result of extraction. However, if the Eq. (8) is not satisfied by the noise signal being analysed, one should verify the accuracy of the extraction result. This can be done by direct comparison of the given noise signal $x[n]$ and the extracted RTS component $s[n]$ and by analyzing the statistical properties of the remaining noise component $v[n]$, which one has obtained in the result of subtraction of the extracted RTS component from the entire noise signal. The identification procedure which has been described has been used and discussed in examination of the low-frequency noise in semiconductor devices. It has been observed by experiments that the RTS extraction results depend strongly on the chosen threshold Δx.

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