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APPROXIMATION METHOD FOR DETERMINING THE PULSE SIGNAL FORM AND ITS INTENSITY MEASUREMENT WITH AN AVAILABLE RANDOM NOISE

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Abstract. *The paper deals with the issues of the operational measurement of a single pulse intensity, as well as the determination of its approximation model. The radar impulse envelope, as well as the peak signal of the analytical instrument, was chosen as the pulse. The pulse square and dispersion were chosen as a measure of intensity. To solve the problem, we use a spline - approximation of discrete samples of the pulse signal. The error of the spline - approximation of the pulse signal discrete values, as well as the error of approximation in the presence of random interference is determined. It is shown that the use of spline approximation reduces the effect of random noise. The characteristics of the proposed method are determined using parabolic¸ as well as cubic spline approximation. The analysis of the error of the considered method caused by the presence of a random additive interference is given. The characteristics of the considered method are determined when analyzing the Gaussian signal. The dependence of the error of the considered method on the intensity of the random noise is determined. The study was conducted for a uniform distribution of random noise. The structure of the system that implements the described method of spline - approximation of the signal samples is described. It is proposed to use the considered approximation method of measuring the pulsed Gaussian signal intensity when solving problems of its detecting against a noise background, as well as determining its boundaries. It is proposed to use the described methods, if necessary, to promptly determine the effective value of a periodic non-harmonic signal (during no more than half of its period) by determining the dispersion of its one half-wave. It is also proposed to use the described methods to determine the informative parameters of a pulse signal (the position of its beginning, end, amplitude).*

Keywords: *signal dispersion, approximation, random noise, discretization, instantaneous*

Introduction

Pulse signals are used for the measurements of information parameters of different processes in many applied tasks. Such typical tasks include radio location and hydrolocation, chromatographic, and spectrometer systems for analysis of different substance compositions, as well as nondestructive test pulse systems and systems for liquid and gas flow parameter determination. In most cases, the pulse signal is detected against the background of random interference for the solution of these problems; herein, the intensity of this will be determined, as well as the shape and main parameters (amplitude, its position on the independent time variable, pulse beginning, and its end) defined.

The same task is required for effective control, as well as for the detection of emergency situations with powerful electrical equipment, when the parameters of periodic non-harmonic signals are determined with urgency within the time no more than half a

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signal period.

Attachments to radiolocation and hydrolocation consider the pulse signal as having a Gaussian shape, and the problem is to detect this against the background of random interferences [1]. In order to determine the information properties of the pulse signal, different methods of its approximation are used, for example, by means of the convolution of two triangular pulses [2].

In electrical engineering applications, the most reliable method used for the power electrical equipment control is the online measurement of such integral properties as effective voltage values and currents in the circuits of powerful electrical equipment, as well as active and reactive power [3–4]. Similar problems will be resolved for the control of powerful nonconventional sources of electric power, as well as of the electric drives of hybrid vehicles [5].

The online determination of emergency and pre-emergency modes of operation of power electrical equipment requires high speed and accuracy in the measurement of integral characteristics of the periodic signal. In this case, of particular importance are the tasks of measuring the effective value of current and voltage in the circuits of powerful electrical installations [6–8].

Measuring systems using digital signal processors can implement direct measurement by means of a signal samples on the number of sampling intervals, a multiple of the period of its first harmonic.

A disadvantage of this method is the significant error of changing the main signal frequency, as a result, the sampling interval may not be a multiple of its period. Furthermore, the use of digital methods with a small number of discrete values of the signal (about 6…10), as well as in the presence of the additive random interference, means that the error of determination of the signal's effective value can be significant [9–12].

Signals formed by analytical measuring instruments (such as chromatographs and spectrometers) also usually represent a sequence of pulses of a certain shape. In some cases, it can be considered that such pulses have a Gaussian shape, while in others they have more complex shapes. When these pulses are approximated by certain functions, the problem of correcting the hardware function of the inertial detector of analytical instruments can be solved [13].

When such signals are processed, their information properties can be determined: the position of the pulse's beginning and end, amplitude on the axis of independent variables (time or wavelength), and intensity (pulse area, dispersion, or root mean square value).

The above tasks are complicated in the presence of additive random interference.

In the most up-to-date systems, the analog-digital conversion signal is performed, while the methods of pulse signal samples approximation at the interval of its existence are used for the solution of the above problem.

Task-setting

In order to reduce the error caused by the additive random interference approximation method is proposed, smoothing the effect of the random interference imposed on the analyzed signal.

Approximation method of determination of the Gaussian pulse signal's effective value without the additive random interference

Now, the method of determination of the Gaussian pulse signal's intensity (in the form of dispersion), using its spline approximation, will be considered. Practically, signal dispersion is determined by its time implementation xc(t).

In a perfect case, the dispersion y_d of signal x_c is equal to:

$$y_d^{ideal} = \int_0^T x_c^2 dt, \qquad (1)$$

where T is the interval of the pulse signal's existence.

Let us consider the task of determination of the pulse signal dispersion on the basis of its discrete values.

The signal can be recovered within the discretization intervals with the certain error by means of the approximation function. In this case, the approximation function coefficients can be used for the determination of signal effective value.

When the described task is resolved, different approximations are used. In [14], the methods of digital harmonic analysis of multicomponent random signals are used; [15] describes systems for the evaluation of the amplitude range of multicomponent random signals.

The use of "smooth" spline functions for the approximation of discrete values of the pulse signal inside the range of its existence appears promising [16, 19], comprising the use of cubic splines for the approximation of noisy data. However, it is reasonable to use the approximation of discrete values not as an end in itself, but as a tool for the determination of the information parameters of the pulse signal (for example, in the pulse area and its dispersion).

Let us consider the use of the parabolic spline function for this purpose, which is described by the following expression on the n-th sampling interval:

$$x_{parab}(t) = a_2[n]t^2 + a_1[n]t + a_0[n], \qquad (2)$$

where a2[n], a1[n], and a0[n] are constant coefficients for the n-th interval.

Coefficients $a_2[n], a_1[n], a_0[n]$ are also determined by the relevant expressions described by one of the digital spline filters. For example, for the five-point parabolic spline filter, these expressions are determined by expressions [13, 18]:

$$\left.\begin{aligned} a_0[n] &= \frac{1}{16}\left(-x_c[n-2]+4x_c[n-1]+10x_c[n]+4x_c[n+1]-x_c[n+2]\right), \\ a_1[n] &= \frac{1}{8t_d}\left(x_c[n-2]-6x_c[n-1]+6x_c[n+1]-x_c[n+2]\right), \\ a_2[n] &= \frac{1}{16t_d^2}\left(-x_c[n-2]+7x_c[n-1]-6x_c[n]-6x_c[n+1]+\right. \\ &\qquad \left. +7x_c[n+2]-x_c[n+3]\right). \end{aligned}\right\} \qquad (3)$$

When using expressions (3), the spline approximation $X_{parab}(t)$ of the signal's samples is determined by the following expression:

$$X_{parab}(t) = \sum_{m=2}^{n+4}\left[\begin{vmatrix} a_2[n](t-nt_d)^2 + a_1[n](t-nt_d)+a_0[n] & if \quad nt_d < t \le (n+1)t_d \\ 0 \quad otherwise & \end{vmatrix}\right]. \qquad (4)$$

It is known that the parabolic spline function does not break down at the 0-th and 1-st derivatives at the sampling intervals boundary; therefore, the use of approximation splines almost does not cause higher harmonic appearances in the signal spectrum recovered by means of such approximations. Furthermore, the digital filter implementing the approximation algorithm has the feature of signal smoothing, on which the additive interference is imposed [19].

The first initial moment of parabolic spline function, approximating a signal in one sampling interval, is determined by the expression:

$$m_{d\,parab} = \int_0^{t_d} \left(a_2[n]t^2 + a_1[n]t + a_0[n] \right) dt = t_d \left(a_2[n]\frac{t_d^2}{3} + a_1[n]\frac{t_d}{2} + a_0^2[n] \right). \tag{5}$$

If the parabolic spline approximation of the pulse signal on its period of existence is determined on the *m* of the sampling intervals, then her first initial moment is:

$$M_{parab} = t_d \left[\sum_{n=1}^{m-2} \frac{1}{3} a_2^2[n] \cdot t_d^2 + \frac{1}{2} a_1[n] \cdot t_d + \frac{1}{3} a_0^2[n] \right]. \tag{6}$$

The expression for the second initial moment of the spline function (i.e., its dispersion) on *n*-th sampling interval is as follows:

$$d_{d\,parab}[n] = \int_0^{t_d} \left(a_2[n]t^2 + a_1[n]t + a_0[n] \right)^2 dt = t_d \left(a_2[n]\frac{t_d^4}{5} + a_2[n]a_1[n]\frac{t_d^3}{2} + a_1^2[n]\frac{t_d^2}{3} + +a_0[n]a_2[n]\frac{2t_d^2}{3} + a_0[n]a_1[n]t_d + a_0^2[n] \right). \tag{7}$$

If the parabolic spline approximation of pulse signal on its interval of existence is determined on *m* sampling intervals, then its dispersion will be expressed in the following way at the signal sampling interval t_d:

$$D_{parab} = t_d \left[\sum_{n=1}^{m} \frac{1}{5} a_2^2[n] \cdot t_d^4 + \frac{1}{2} a_1[n]a_2[n] \cdot t_d^3 + \frac{1}{3} a_1^2[n] \cdot t_d^2 + \frac{2}{3} a_0[n]a_2[n] \cdot t_d^2 + a_0[n]a_1[n] \cdot t_d + a_0^2[n] \right]. \tag{8}$$

If required, from here the root mean square value of the pulse signal can be determined as:

$$y_{rms\,spl} = \sqrt{D_{parab}}.$$

Expression (3) demonstrates that in order to determine the coefficients of spline approximation of signal x_c on the interval of its existence, two additional sampling intervals will be used to the left of the approximation interval (on at half signal period), as well as two additional sampling intervals to the right of the approximation interval.

Thus, the spline approximation of the signal's discrete samples is determined at the interval [$2t_d$, $(T+2t_d)$].

Expressions (3), (5), and (6) are implemented by means of microprocessor controllers for the determination of signal dispersion during its interval of existence.

Let us consider the use of cubic spline approximations for this purpose, which is described by means of the following expression on the n-th sampling interval:

$$x_{cub}(t) = a_3[n]t^3 + a_2[n]t^2 + a_1[n]t + a_0[n], \tag{9}$$

where $a_3[n]$, $a_2[n]$, $a_1[n]$, $a_0[n]$ are constant coefficients for n-th interval.

Coefficients $a_3[n],\ a_2[n],\ a_1[n],\ a_0[n]$ are determined using the relevant expressions for one of the digital spline filters. For example, these expressions are determined by the following expressions for the five-point cubic spline filter [13, 18]:

$$\left.\begin{aligned}
a_0[n] &= \frac{1}{36}\left(-x_c[n-2] + 4x_c[n-1] + 10x_c[n] + 4x_c[n+1] - x_c[n+2]\right),\\
a_1[n] &= \frac{1}{12t_d}\left(x_c[n-2] - 8x_c[n-1] + 8x_c[n+1] - x_c[n+2]\right),\\
a_2[n] &= \frac{1}{12t_d^2}\left(-x_c[n-2] + 10x_c[n-1] - 18x_c[n] + 10x_c[n+1] - [n+2]\right),\\
a_3[n] &= \frac{1}{36t_d^2}(x_c[n-2] - 11x_c[n-1] + 28x_c[n] - 28x_c[n+1] + 11x_c[n+2] - x_c[n+3]).
\end{aligned}\right\} \tag{10}$$

When using coefficients (10), the cubic spline approximation $X_{cub}(t)$ of the signal's samples is defined by the expression:

$$X_{cub}(t) = \sum_{m=2}^{n+4}\left[\begin{vmatrix} K[n] & if \quad nt_d < t \le (n+1)t_d \\ 0 & otherwise \end{vmatrix}\right], \tag{11}$$

where $K[n] = a_3[n](t-nt_d)^3 + a_2[n](t-nt_d)^2 + a_1[n](t-nt_d) + a_0[n]$.

The initial moment of the cubic spline function, the approximation signal on n-th sampling interval is expressed as follows:

$$m_{d\,cub} = \int_0^{t_d}\left(a_3[n]t^3 + a_2[n]t^2 + a_1[n]t + a_0[n]\right)dt = $$
$$= t_d\left(a_3[n]\frac{t_d^3}{4} + a_2[n]\frac{t_d^2}{3} + a_1[n]\frac{t_d}{2} + a_0^2[n]\right). \tag{12}$$

If the cubic spline approximation of pulse signal in its interval of existence is determined on m discrete areas, then its initial moment is equal to:

$$M_{cub} = t_d \left[\sum_{n=1}^{m-2} \frac{1}{4} a_3[n] \cdot t_d^3 + \frac{1}{3} a_2[n] \cdot t_d^2 + \frac{1}{2} a_1[n] \cdot t_d + a_0[n] \right].$$

(13)

The expression for the second initial moment of the cubic spline function (i.e., its dispersion) on n-th sampling interval is determined by the expression:

$$d_{cub}[n] = \int_0^{t_d} \left(a_3[n]t^3 + a_2[n]t^2 + a_1[n]t + a_0[n] \right)^2 dt$$

After conversion, this expression takes the following form:

$$d_{cub}[n] = t_d \left(\left(a_3[n]\right)^2 \frac{t_d^6}{7} + a_2[n]a_3[n]\frac{t_d^5}{3} + 2a_1[n]a_3[n]\frac{t_d^4}{5} + \left(a_2[n]\right)^2 \frac{t_d^4}{5} + a_0[n]a_3[n]\frac{t_d^3}{2} + \right.$$

$$\left. + a_1[n]a_2[n]\frac{t_d^3}{2} + 2a_0[n]a_2[n]\frac{t_d^2}{3} + \left(a_1[n]\right)^2 \frac{t_d^2}{3} + a_0[n]a_1[n]t_d + \left(a_0[n]\right)^2 \right).$$

(14)

If the cubic spline approximation of the pulse signal in its interval of existence is determined in m samples, then for the sampling interval t_d its dispersion is determined by the expression:

$$D_{cub} = \sum_{n=1}^{m} \alpha_{2d\ cub}[n]. \qquad (15)$$

Analysis of the characteristics of the considered method without random interference

Let us consider the task of determining the Gaussian signal dispersion of unit amplitude as an example:

$$x_c(t) = \exp\left[-\frac{(t-7)^2}{3} \right], \qquad (16)$$

presented with 12 samples.

A graph of this signal is presented in Fig. 1.

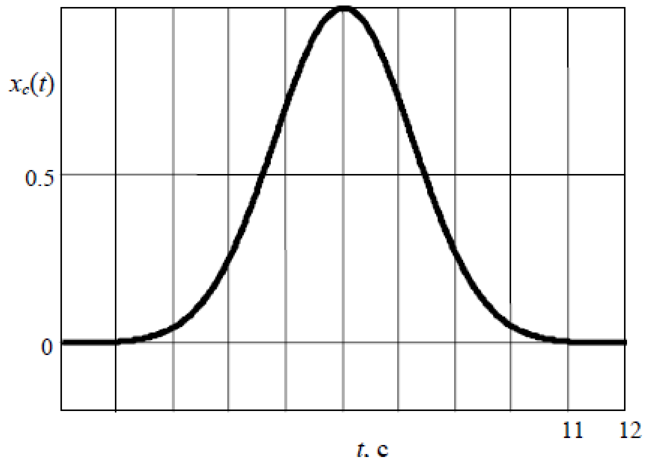

Fig. 1. Diagram of a Gaussian pulse signal.

The graphs of the parabolic and cubic spline approximations of the pulse signal's samples, plotted using expressions (4) and (11), are presented in Fig. 2.

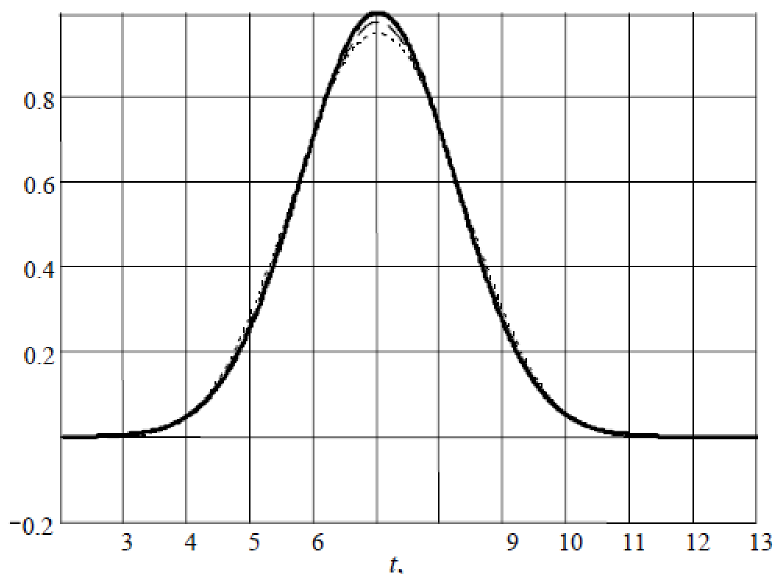

Fig. 2. Diagrams of parabolic X_{parab} and cubic X_{cub} spline approximations of Gaussian pulse signal $x_c(t)$: samples

——— signal $x_c(t)$;

.... parabolic approximation X_{parab};

- - - - - cubic approximation X_{cub}

Dependencies of the errors of pulse signal approximation with parabolic and cubic spline are presented in Fig. 3.

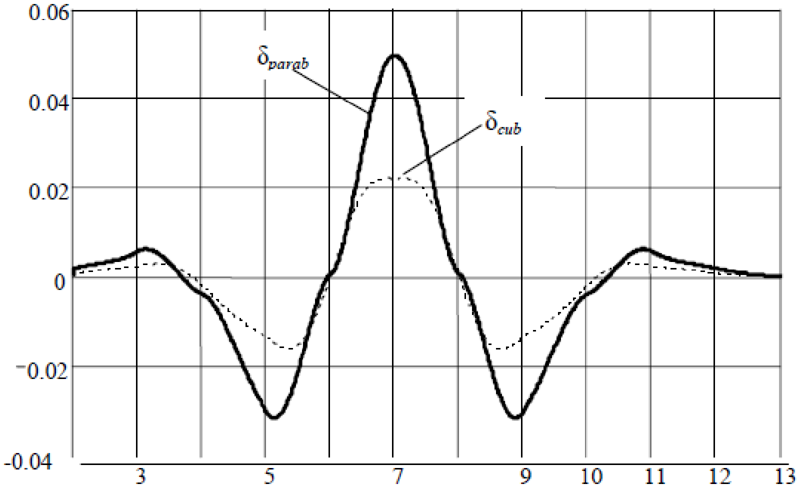

Fig. 3. Dependence of the error of the Gaussian pulse signal samples approximation of parabolic and cubic splines (δ_{parab} and δ_{cub} accordingly).

Examination of these diagrams demonstrates that with about 10 samples of selected pulse signal, the error of approximation with parabolic spline does not exceed 5%, and cubic - 2%.

If required, spline approximation of the pulse signal's samples can be recovered in continuous form by means of the structures based on integrators, scaling amplifiers, and an analogous shift register [20].

Let us consider the possibility of determining the pulse signal moments of the first and second order (16).

The true value of the Gaussian pulse signal moment of the first order, i.e., its area, is determined with the following expression:

$$M_{ideal} = \int_0^{13} x_c(t)dt = 3,07. \quad (17)$$

The true value of the pulse signal's moment of the second order, i.e., its dispersion, is determined with the expression:

$$D_{ideal} = \int_0^{13} x_c^2(t)dt = 2,171. \quad (18)$$

When using the parabolic spline approximation of the pulse signal's discrete values (11), its first-order moment is determined with expression (6) and is equal:

$$M_{parab} = 3,071,$$

while its dispersion determination with (8) is equal:

$$D_{parab} = 2,111. \; D_{parab} = 2,111. \quad (19)$$

Errors of determination of the pulse signal moments M_1 and D_2 with parabolic spline approximation of its samples are expressed as follows:

$$\delta M_{parab} = \frac{M_{ideal} - M_{parab}}{M_{ideal}} \cdot 100\%, \qquad \delta D_{parab} = \frac{D_{ideal} - D_{parab}}{D_{ideal}} \cdot 100\%$$

(20)

and are equal respectively:

$$\delta M_{parab} = 0,03\%, \quad \delta D_{parab} = 2,7\%. \tag{21}$$

When using the cubic spline approximation of the Gaussian pulse signal's samples (11), its first-order moment is determined with expression (13) and is equal:

$$M_{cub} = 3,071,$$

and its dispersion defined by the expression (15) is:

$$D_{cub} = 2,111.$$

Errors of determination of the Gaussian pulse signal moments M_1 and D_2 with cubic spline approximation of its samples are defined with expressions similar to (20) and are equal respectively:

$$\delta M_{cub} = 0,013\%, \quad \delta D_{cub} = 1,5\%. \tag{22}$$

Analysis of the characteristics of the considered method with random interference

In determining the Gaussian signal dispersion (16) of unit amplitude with random interference of range 0.1 having the equipartition law, the graph of such a signal is presented in Fig. 4.

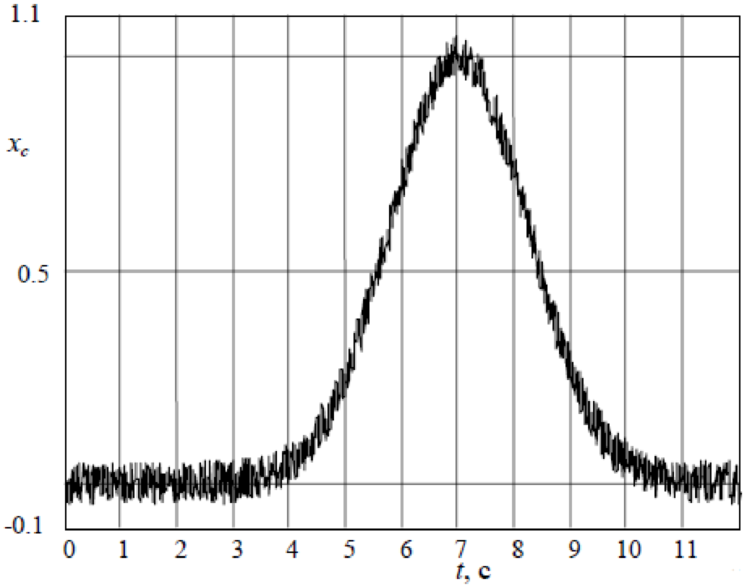

Fig. 4. Gaussian pulse signal with interference.

As in the previous example, the signal is presented with 12 samples with imposed additive random interference. Diagrams of parabolic and cubic spline approximation of such signals are presented on Fig. 5.

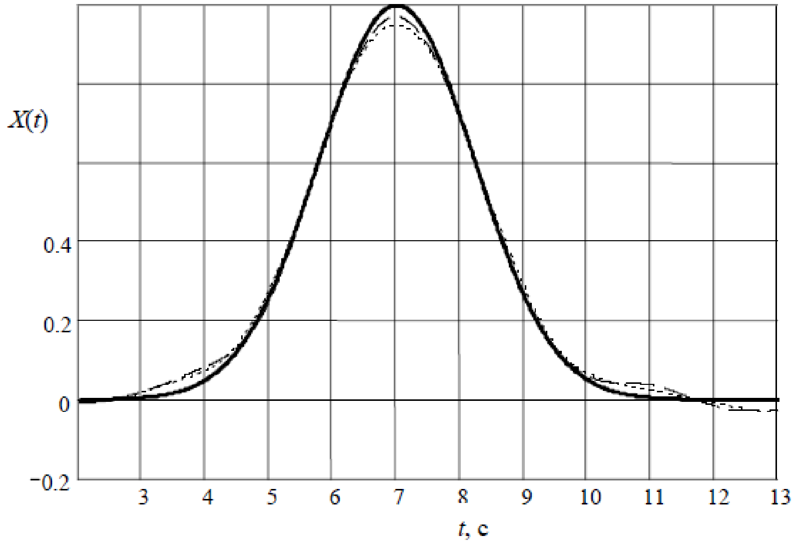

Fig. 5. Diagram of parabolic X_{parab} and cubic X_{cub} spline approximations of Gaussian pulse signal $x(t)$ samples with additive random interference:

——— signal $x(t)$;

.... approximation X_{parab};

- - - - - approximation X_{cub}

Diagrams of errors of spline approximation of signal samples with interference are presented on Fig. 6.

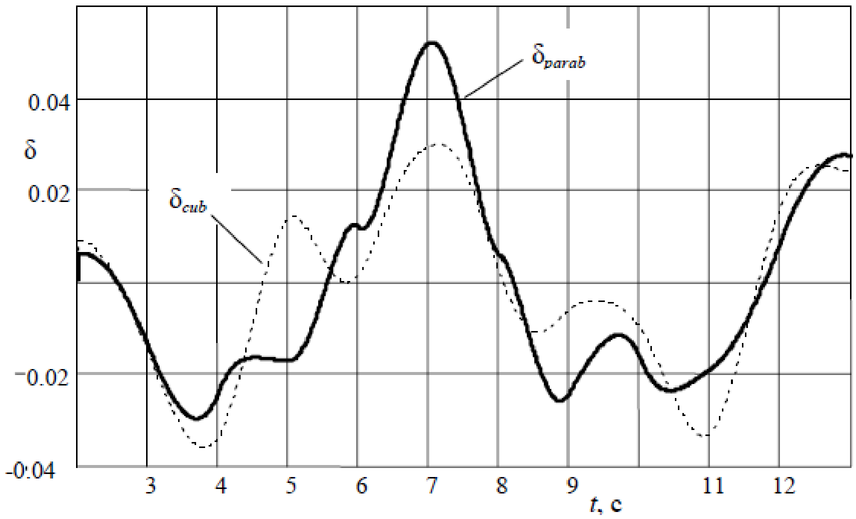

Fig. 6. Dependence of the error of Gaussian pulse signal samples approximation with parabolic and cubic splines error (δ_{parab} and δ_{cub} accordingly).

Fig. 3 and Fig. 6 demonstrate that despite the significant interference, the errors of the signal spline approximation insignificantly increased.

When using the parabolic spline approximation of the pulse signal's samples (11) with interference, its first-order moment is determined with expression (6) and amounts to:

$$M_{parab} = 3{,}182,$$

while its dispersion determination with (8) amounts to:

$$D_{parab} = 2{,}147.$$

Errors of determination of the pulse signal moments M_{parab} and D_{parab} with parabolic spline approximation of its samples are determined with expressions (20) and are equal respectively:

$$\delta M_{parab} = 3{,}6\%, \quad \delta D_{parab} = 1{,}1\%. \tag{23}$$

When using the cubic spline approximations of the pulse signal's samples (11), its first-order moment is determined with expression (13) and amounts to:

$$M_{cub} = 3{,}186,$$

while its dispersion determining with (15) amounts to:

$$D_{cub} = 2{,}17.$$

Errors of determination of the pulse signal moments M_{cub} and D_{cub} with parabolic spline approximation of its discrete values with imposed additive random interference are determined with expressions similar to (20) and are equal respectively:

$$\delta M_{cub} = 3{,}8\%, \quad \delta D_{cub} = 0{,}03\%. \tag{24}$$

Let us consider the properties of the direct digital method of determination of moments M and D of the pulse signal with imposed additive random interference.

These are determined with the following expressions:

$$M_{\Sigma} = \sum_{n=1}^{m} x[n], \quad D_{\Sigma} = \sum_{n=1}^{m} x^2[n]. \tag{25}$$

For this example, these values are equal respectively:

$$M_{\Sigma} = 3{,}24; \quad D_{\Sigma} = 2{,}21.$$

Errors of determination of pulse signal moments M_{cub} and D_{cub} with imposed additive random interference when using expression (25) are equal respectively:

$$\delta M_{\Sigma} = 5{,}5\%, \quad \delta D_{\Sigma} = 1{,}7\%. \tag{26}$$

Conclusions

In this paper, it was shown that:

1. The use of spline approximation of the Gaussian pulse signal samples allows recovery of the signal shape with relatively small errors and a fairly small number of samples (about 10).
2. The Spline approximation of the pulse signal's samples allows for the

determination of the values of the first and second initial moments (expectation and dispersion) of the pulse signal with a small error.

3. In the case of the random additive interference, the spline approximation of the pulse signal's samples restores its shape-correcting interference, which makes the determination of the signal's information parameters fairly easy (position of the pulse signal at the beginning, top, and end of the independent variable axis).
4. A comparison of errors (24), (25), (26) of different methods allows one to conclude that in the case of random interference, the direct method (25) of determination of the pulse signal moment has a significantly higher error in comparison to the methods of parabolic and cubic spline approximation of the signal's samples.

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АППРОКСИМАЦИОННЫЙ МЕТОД ОПРЕДЕЛЕНИЯ ФОРМЫ И ИЗМЕРЕНИЯ ИНТЕНСИВНОСТИ ИМПУЛЬСНОГО СИГНАЛА ПРИ НАЛИЧИИ СЛУЧАЙНОЙ ПОМЕХИ

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Аннотация. *Рассмотрены вопросы оперативного измерения интенсивности одиночного импульса, а также определения его аппроксимационной модели. В качестве импульса выбрана огибающая радиолокационного импульса, а также пик сигнала аналитического прибора. В качестве меры интенсивности выбрана площадь, а также дисперсия импульса. Для решения поставленной задачи используется сплайн-аппроксимация дискретных значений импульсного сигнала. Определена погрешность сплайн-аппроксимации дискретных значений импульсного сигнала, а также погрешность аппроксимации при наличии случайной помехи. Показано, что использование сплайн-аппроксимации снижает влияние случайной помехи. Определены характеристики предложенного метода при использовании параболической, а также кубической сплайн-аппроксимации. Приведен анализ погрешности рассмотренного метода, вызванной наличием случайной аддитивной помехи. Определены характеристики рассмотренного метода при анализе гауссового сигнала. Определена зависимость погрешности рассмотренного метода от интенсивности случайной помехи. Исследование проведено для равномерного закона распределения случайной помехи. Описана структура системы, реализующей описанный метод сплайн-аппроксимации дискретных значений сигнала. Предложено использовать рассмотренный аппроксимационный метод измерения интенсивности импульсного гауссового сигнала при решении задач обнаружения сигнала на фоне помех, а также определения его границ. Предложено использовать описанные методы при необходимости оперативного определения эффективного значения периодического негармонического сигнала (за время не более половины его периода) путем определения дисперсии его одной полуволны. Предложено также использовать описанные методы для определения информативных параметров импульсного сигнала (его положения начала, конца, амплитуды).*

Ключевые слова: *дисперсия сигнала, аппроксимация, случайная помеха, дискретизация, мгновенное значение, сплайн, импульсный сигнал.*

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