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An algorithm of position-binary technology for controlling the beginning and dynamics of accidents of sucker rod pumping units

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A B S T R A C T

In recent years, diagnostics of the state of an object using the NOISE technology has shown incomparable advantages in recognizing state changes and has been widely used in various fields. It is important here to determine the beginning of a change in the technical condition and the dynamics of its development before the accident. The article deals with the problem of determining the onset of an accident and its dynamics of development in the technical condition of sucker rod pumping units in oil production by mechanized methods. We propose algorithms for calculating the estimates of informative attributes of a cyclic signal, both decomposed into position-binary components and saved in the form of an array, and in the course of measurement and analog-to-digital conversion without saving. Real dynamometer charts of sucker rod pumping units are taken as signals.

1. Introduction

The economies of most of the former Soviet Union countries are based on the extraction and export of fuel natural resources, mainly oil and gas. Such companies as Gazprom, Rosneft and Transneft in the Russian Federation are state-forming. A similar situation is observed in other CIS states.

In the former Soviet Union, the main countries involved in oil production are the Russian Federation and the Caspian countries, Azerbaijan, Kazakhstan and Turkmenistan. Small amounts of oil are also produced in Belarus and Ukraine [1].

It is known that the main method of artificial lift is the use of sucker rod pumping units (SRPU) and submersible electric centrifugal pumps (ESP). For instance, in the Russian Federation 41% of wells are operated by SRPU and 54% by ESP [2]. The published data indicate that more than 85% of wells with artificial lift in USA are equipped with ESP. The use of ESPs is popular because of their simplicity, reliability and ability to be used in a wide range of operating conditions [3].

However, due to the reduction of oil reserves, increase of waterflooding of formations, and well downtime due to untimely diagnostics of the equipment condition, the profitability of oil production by SRPU is sharply declining. Issues of quality and exact diagnostics of malfunctions of

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SRPU are an important link in ensuring profitability, especially of long-operated oil fields. Timely detection of malfunctions of SRPU and taking necessary measures for their elimination will provide the necessary level of stabilization of oil production.

As is known, the most widespread and common way of control of operating modes and diagnostics of malfunctions of underground equipment of wells operated by SRPUs is dynamometer chart. A dynamometer chart is the dependence $P(S)$ of the force in the point of the rod hanger of the SRPU on the S movement of the rod hanger center. The process of taking and analyzing the curve of the force of P function on the S movement of the rod hanger center is called dynamometry [4].

All these methods allow determining individual malfunctions in the technical condition of the controlled objects, when they have clearly pronounced forms. However, the qualitatively new technologies for analyzing noise of noisy signals developed at the Institute of Control Systems of ANAS give reason to believe that their application to the signal of force in the rod hanger center will allow determining the beginning and dynamics of the development of accidents of SRPU [5-7].

2. Problem statement

Developing an algorithm of computer simulation of the beginning and dynamics of accidents of SRPU for operative informing of the oil field personnel about changes in the state of well operation, using the position-binary technology of analysis of noisy signals of force in the rod hanger center.

3. Problem solution

The theoretical foundations of Noise control of the beginning and dynamics of accidents development by the position-binary technology are given in [7, p.92]. It is shown that at the normal stable technical state of the cyclic object from the analog signal $X(t)$ in analog-to-digital conversion $X(i\Delta t)$ in each j-th bit will form sets of combinations of mean frequencies of the position-binary signal (PBS) $q_j(i\Delta t)$. The change of the technical state of the object will lead to their change, which will mean the beginning of the latent period of the accident, and the subsequent changes will indicate the dynamics of the accident development.

Control of the beginning of accidents by the position-binary technology. The essence of PBS is that the signals (Fig. 1 *a*) in the process of analog-to-digital conversion are transformed into position-binary signals (PBS) (Fig. 1 *b, c*), containing in each bit a sequence of pulses, which adequately reflect changes in the form of the original signal [8]. Here, it is proposed to use parameters of obtained PBS pulses as informative attributes.

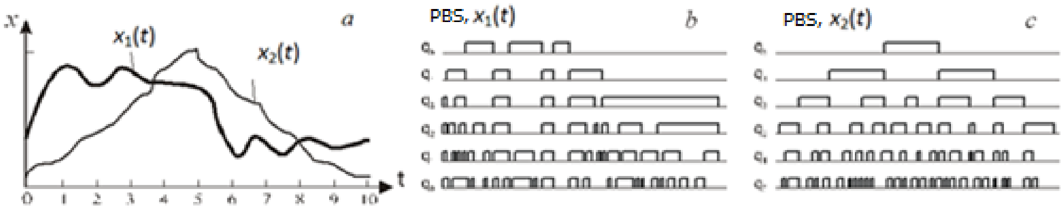

Fig.1. Signals (*a*) and their corresponding PBS (*b*) and (*c*).

From the pulse technique [9, p.8] it is known that the main parameters of pulses are: duration, power, pulse repetition period (or its inverse value, pulse frequency), fill factor (or its inverse value, duty cycle), mean value of pulse oscillation and mean pulse power. Obviously, in our case the pulses are created from logical '1' and '0'. Here, taking into account their specific features, in the first approximation, it is enough to consider the following parameters for a certain time interval to determine the beginning of the latent period of change in the technical state of the object:

f_{q_j} – mean pulse frequency in j-th bit;

k_{q_j} – coefficient of the ratio of mean estimates of pulse duration to mean estimates of pause period in j-th bit;

K_{3q_j} – pulse fill factor in j-th bit.

Obviously, a change in the technical state of the object will lead to a change in the bits of the PBS combination and estimates of their mean frequencies f_{q_0}, f_{q_1}, ..., f_{q_m}, which are determined from the expressions:

$$f_{q_0} = \frac{1}{<T_{q_0}>}, \quad f_{q_1} = \frac{1}{<T_{q_1}>}, \quad f_{q_2} = \frac{1}{<T_{q_2}>}, \dots, \quad f_{q_m} = \frac{1}{<T_{q_m}>} \text{ or } f_{q_j} = \frac{1}{<T_{q_j}>}, \tag{1}$$

where $< T_{q_j} >= \frac{1}{\Pi}\sum_{k=1}^{n} T_{q_j k}$ is the mean period of pulses in the j-th bit; $T_{q_j k}$ is the period of the *k*-th pulse in the j-th bit.

Here, the ratio of the mean estimates of the pulse duration $T_{1q_j} >$ to the mean estimates of the pause period $<T_{0q_j} >$ of each bit is a non-random value and expresses the nature of the resulting position-binary signal (PBS):

$$k_{q_0} = \frac{<T_{1q_0}>}{<T_{0q_0}>}, \quad k_{q_1} = \frac{<T_{1q_1}>}{<T_{0q_1}>}, \quad k_{q_2} = \frac{<T_{1q_2}>}{<T_{0q_2}>}, \dots, \quad k_{q_m} = \frac{<T_{1q_m}>}{<T_{0q_m}>} \text{ or } k_{q_j} = \frac{<T_{1q_j}>}{<T_{0q_j}>}, \tag{2}$$

where $< T_{1q_j} >= \frac{1}{n}\sum_{k=1}^{n} T_{1q_j k}$ and $< T_{0q_j} >= \frac{1}{n}\sum_{k=1}^{n} T_{0q_j k}$ are the mean values of pulse duration and pause in the j-th bit, respectively; $T_{1q_j k}$ and $T_{0q_j k}$ are duration and pause of the *k*-th pulse in the j-th bit, respectively.

Note also that the ratios of the mean estimates of pulse durations $<T_{1q_j} >$ to the mean estimate of pulse periods $< T_{q_j} >$ of each bit is also a non-random value, and expresses the mean pulse fill factor of the obtained position-binary signal (PBS):

$$K_{3q_j} = \frac{<T_{1q_j}>}{<T_{q_j}>}; \tag{3}$$

Consequently, using the informative attributes f_{q_j},k_{q_j} and K_{3q_j} of PBS we can control changes in the technical condition of the object, that is, the beginning of a hidden period of changes in the technical condition of the object.

It is obvious that if during the observation time *T* we perform analog-to-digital conversion of the signal with interval Δt into *N* discrete values and decompose them into position-binary components, then the mean frequency f_{q_j} of created pulses n_{cq_j} in the *j-th* bit will be determined by the number of pairwise transitions 0→1 and 1→0 or vice versa of the same bit. For instance, for Fig. 1 *b* $f_{q_5} \sim n_{cq_5} = 3$, $f_{q_4} \sim n_{cq_4} = 4$, $f_{q_3} \sim n_{cq_3} = 6$, $f_{q_2} \sim n_{cq_2} = 11$, $f_{q_1} \sim n_{cq_1} = 18$, $f_{q_0} \sim n_{cq_0} = 20$). The number of repeating ones will create the pulse duration $T_{1q_j k}$, the number of repeating zeros will create a pause $T_{0q_j k}$, and the time period between two adjacent transitions of 0→1 or 1→ 0 – pulse period $T_{q_j k}$.

If in formulas (2) and (3) the numerator and denominator are multiplied by the number of pulses n of the PBS, then we obtain, respectively:

$$K_{q_j}=\frac{\sum_{k=1}^{n}T_{1q_jk}}{\sum_{k=1}^{n}T_{0q_jk}}=\frac{T_{1q_j}}{T_{0q_j}}\text{ or }K_{q_j}=\frac{N_{1q_j}}{N_{0q_j}}; \tag{4}$$

$$K_{3q_j}=\frac{\sum_{k=1}^{n}T_{1q_jk}}{\sum_{k=1}^{n}T_{q_jk}}=\frac{T_{1q_j}}{T}\text{ or }K_{3q_j}=\frac{N_{1q_j}}{N}. \tag{5}$$

Thus, the problem of calculating the parameters of PBS pulses in the j-th bit comes down to:

– for the coefficient of the mean pulse/pause ratio, calculating the ratio of the number of ones of the same bit N_{1q_j} to the number of zeros N_{0q_j};

– for the fill factor, calculating the ratio of the number of units of the same bit N_{1q_j} to the total sampling number N for the observation period.

Consider the possible options for creating an algorithm for calculating the estimate of informative attributes f_{q_j},k_{q_j} and K_{3q_j}.

1. The measured signal after the analog-to-digital conversion is stored in the computer memory as an array (6) and it is required to determine the above informative attributes.

$$\begin{vmatrix} q_M,1 & \cdots & q_M,i & \cdots & q_M,\mathrm{N} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ q_j,1 & \cdots & q_j,i & \cdots & q_j,\mathrm{N} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ q_1,1 & \cdots & q_1,i & \cdots & q_1,\mathrm{N} \end{vmatrix} \tag{6}$$

where $j=1\div\mathrm{M}$; M is the effective number of bits of the analog-to-digital converter (ADC); $i=1\div\mathrm{N}$; N is the number of measurements.

For this case, we can propose the following algorithm (Fig. 2) for calculating the estimates of informative attributes f_{q_j}, k_{q_j} and K_{3q_j}.

Here, X is an array containing the original information of the signals read from the ADC; i is the index of the array X; N is the number of read signals contained in the array X; j is the bits of signal processing; M is the effective number of bits of the ADC; a is the auxiliary variable (takes values '0' or '1'), used to determine the value of the j-th bit of the signal; d is the auxiliary variable, used to store the number of identical bits in a certain interval of check; f_{q_j} is the variable that contains the number of transitions from '0' to '1' and from '1' to '0' in the j-th bit; k_0 is the variable that contains the sums of zeros in in the j-th bit; k_1 is the variable which contains the sums of ones in the j-th bit; Z is a three-dimensional array containing the values of f_{q_j}, K_{q_j} and K_{3q_j} for each bit:

$$Z:=[(f_{q_1},K_{q_1},K_{3q_1}),(f_{q_2},K_{q_2},K_{3q_2}),\ldots].$$

The algorithm consists of the following blocks: 1 – setup block; 2 – assignment block; 3 – block of comparison of the j-th bit of the array $X[i]$ with the value of variable a; the 4 – block of determination of the value of the variable a, i.e., $a=$ '1' or $a=$ '0'; 5 – block of calculation of f_{q_j} and N_{1q_j}; 6 – block of calculation of N_{0qj}; 7 – block of inversion of the variable a and assignment of 1 to d; 8 – block of incrementing index i; 9 – block of checking if the end of the array is reached; 10 – block of calculation of X; 10 – block of calculation of the values of the variables f_{q_j}, K_{q_j} and K_{3q_j} and writing them in the appropriate places in the array Z; 11 – block of incrementing index j; 12 – block of checking if all bits have been considered; 13 – block of incrementing of the variable d; 14 – block of checking the end of the array X.

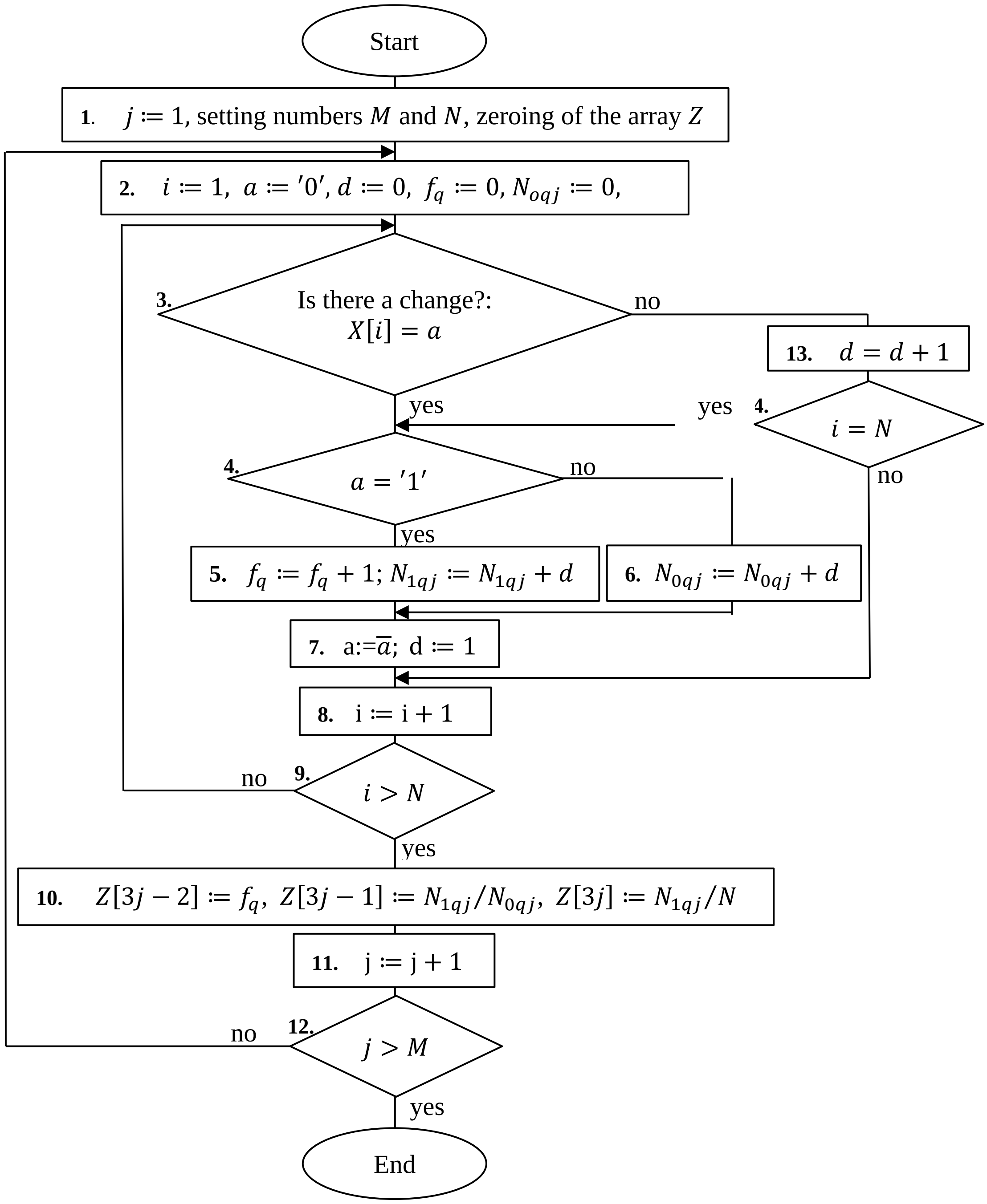

Fig. 2. Algorithm for calculating the estimates of the informative attributes f_{qj}, k_{qj} and K_{3qj} of a signal decomposed into positional-binary components and saved as an array.

The algorithm operates as follows:

In block 1 the variable j is assigned 1, which means that the check starts from the 1st bit, the number N is assigned to the number of signals which were read from ADC to calculate the estimate of informative attributes, the number M, the effective number of bits of the ADC, for instance, $M = 12$. The three-dimensional array for storing the informative attributes f_{q_j}, K_{q_j} and K_{3q_j} is also zeroed: $Z[(3j-2),(3j-1),3j] := 0$.

In block 2 the variable i is assigned 1. This means that the check starts with the first element of the array X. In the variable a at the beginning of each bit check is written '0', the values of the variables d, f_{q_j}, N_{0q_j} and N_{1q_j}: $a := $ '0', $d := 0$, $f_{q_j} \coloneqq 0$, $N_{0q_j} \coloneqq 0$, $N_{1q_j} \coloneqq 0$.

In block 3 the j-th bit of the array $X[i]$ is compared with the value of the variable a. If there is a mismatch, it goes to block 4, otherwise it goes to block 13, where 1 is added to the variable d, which means one more identical bit. Next, after block 13, block 14 follows, where it is checked if the checked element of the array X was the last element in the array. If yes, then it proceeds to block 4, otherwise to block 8.

Block 4 checks the value of the variable a. If this value is equal to '1' the transition to block 5 takes place, otherwise the transition to block 6 takes place.

Going to block 5 means a complete "beat" has been completed, i.e., there has been a transition from '0' to '1' and from '1' to '0'. Therefore, one is added to the variable f_{q_j}. Also, the variable N_{1q_j} is incremented by d: $f_{q_j} \coloneqq f_{q_j} + 1$, $N_{1q_j} \coloneqq N_{1q_j} + d$. Go to block 7.

In block 6 the variable N_{0q_j} is incremented by d: $N_{0q_j} \coloneqq N_{0q_j} + d$. Go to block 7.

In block 7 the value of the variable a is inverted, $a \coloneqq \overline{a}$. Also the variable d is assigned a 1: $d \coloneqq 1$. Go to block 8.

In block 8 the value of the index i is increased by one. Go to block 9.

Block 9 checks if the end of the array X is reached. If the end of the array X is reached, go to block 10, otherwise go to block 3.

In block 10 for each of j-th bit the values $K_{q_j} \coloneqq N_{1q_j}/N_{0q_j}$ and $K_{3q_j} \coloneqq N_{1q_j}/N$ are calculated.

Then the values of these variables, as well as the variable fq are written in the array Z:

$$Z[3j-2] \coloneqq f_q,\ Z[3j-1] \coloneqq N_{1q_j}/N_{0q_j},\ Z[3j] \coloneqq N_{1q_j}/N.$$

After that, go to block 11.

In block 11 the value of the variable j is increased by one. Go to block 12.

Block 12 checks whether the last bit has been reached. If not, go to block 2, otherwise the process comes to an end.

2. The controller of the measuring device has a limited memory and has no possibility to store the array of the measured signal. In this case, it is necessary to calculate the above-mentioned informative attributes in the course of measurement, after the analog-to-digital conversion.

$$\begin{vmatrix} q_j, \mathrm{i} \\ \vdots \\ q_j, \mathrm{i} \\ \vdots \\ q_j, \mathrm{i} \end{vmatrix} \equiv \begin{vmatrix} q_M, i+1 \\ \vdots \\ q_j, i+1 \\ \vdots \\ q_1, i+1 \end{vmatrix}$$

Comparison of the values of the positions q_j, i and $q_j, i+1$, where $\mathrm{j} = 1 \div \mathrm{M}$; and $i = 1 \div \mathrm{N}$; are natural numbers, M is the maximum number of bits of the ADC, N is the number of measurements.

For this case, we can propose the following algorithm (Fig. 3) for calculating the estimates of the informative attributes f_{q_j}, K_{q_j} and K_{3q_j}.

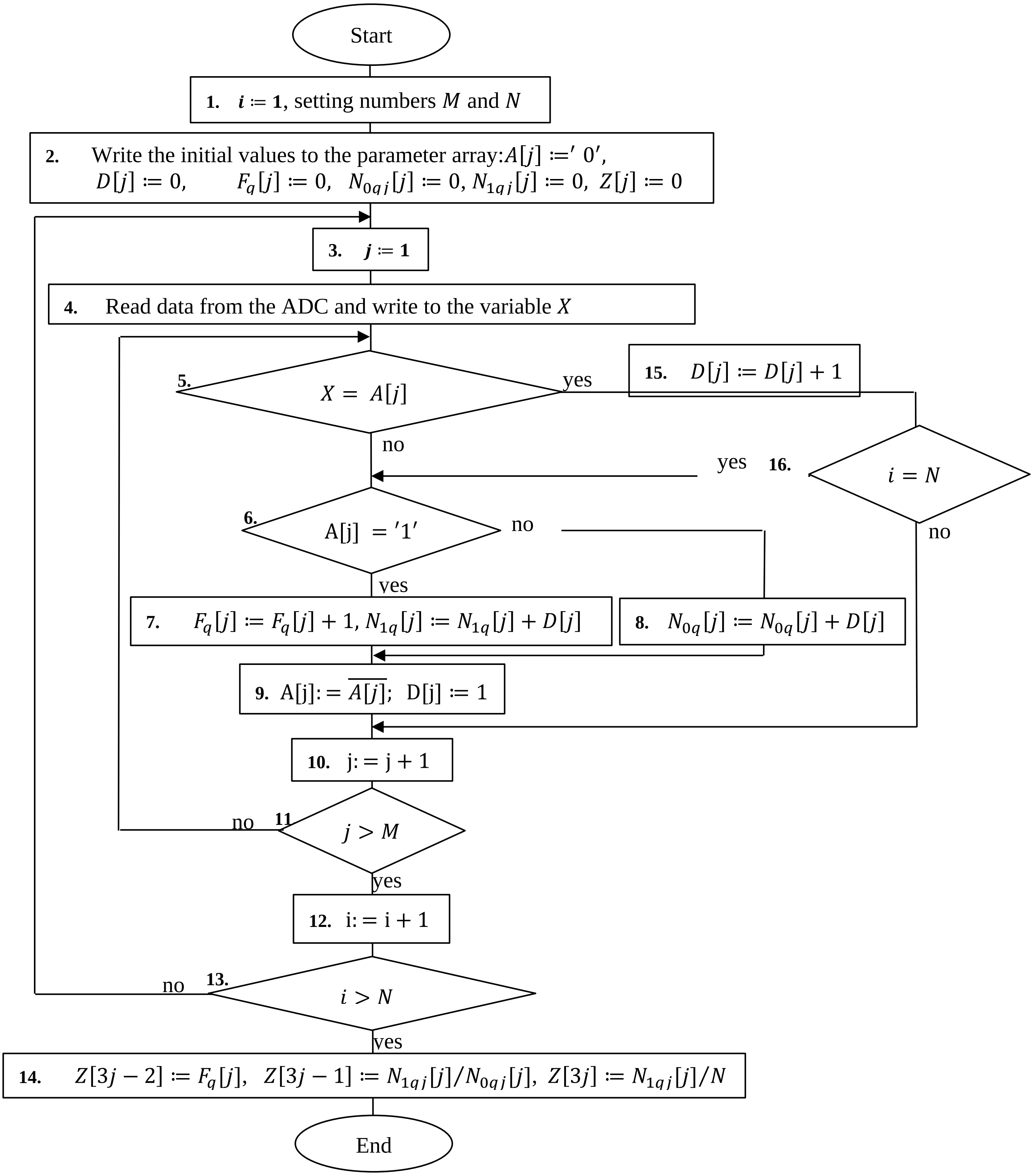

Fig. 3. Algorithm for calculating the estimate of the informative attributes f_{qj}, k_{qj} and K_{3qj} of the signal in the course of measurement and analog-to-digital conversion.

Here, X is a variable containing the information read from the ADC; i is the index of the read signals; N is the maximum amount of information required to read from the ADC; j is the current processing bit; M is the effective number of bits of the ADC; A and D are auxiliary arrays, F_{q_j}, N_{0q_j}, N_{1q_j} are the arrays used to calculate the estimates of informative attributes. All these arrays have an index j and the number of elements of all these arrays is equal to M. For each of j-th bit the above arrays have certain values. The array A takes values '0' or '1' and is used to determine signal values by comparison. The array D is used to store the number of identical bits in a certain checking interval. F_q is the array containing the number of signal transitions from '0' to '1' and from '1' to '0'. The array N_{0q_j} contains the number of zeros for each of j-th bits. The array N_{1q_j} array contains the number of ones for each of the j-th bits. Z is a three-dimensional array containing the values of f_{q_j}, and the calculated values K_{q_j} and K_{3q_j} for each bit:

$$Z \coloneqq [(f_{q_1}, K_{q_1}, K_{3q_1}), (f_{q_2}, K_{q_2}, K_{3q_2}), \dots].$$

The algorithm consists of the following blocks: 1 – block of setting the variables i, M, N; 2 – block of writing of initial values in array of parameters; 3 – block of assignment of one to the variable j; 4 – block of reading of the next data from the ADC and writing into the variable X; 5 – block of comparison of the j-th bit of the variable X with the value of the variable $A(j)$; 6 – block of determination of the variable $A(j)$, i.e., $A(j) = $ '1' or $A(j) = $ '0'; 7 – block of calculation of the value of the variable $F_q[j]$, $N_{1qj}[j]$; 8 – block for determination of the values of the variable $N_{0qj}[j]$; 9 – block of inversion of the variable $A(j)$ and assignment of 1 to $D(j)$; 10 – block of incrementing the index j; 11 – block checking if all bits have been checked; 12 – block of incrementing the index i; 13 – block of checking if all information has been read from the ADC; 14 – block of calculation of the values of the variables f_{q_j}, k_{q_j} and k_{3q_j} for all j bits and writing them in the appropriate places in the array Z; 15 – block of incrementing the variable $D(j)$; 16 – block for checking the end of reading.

The algorithm operates as follows:

In block 1 one is assigned in the variable i, which means the beginning of reading of a signal from the ADC, also the number N, the required number of signals which will be read from ADC to calculate the estimate of informative attributes, is sets. The number M, the effective number of bits of the ADC, is also set, e.g., $M \coloneqq 12$.

In block 2, in the parameters consisting of arrays, their initial values are written: $A(j) := $ '0', $D(j) := 0$, $F_q[j] \coloneqq 0$, $N_{0q_j}[j] \coloneqq 0$, $N_{1q_j}[j] \coloneqq 0$. The three-dimensional array Z is also zeroed: $Z[3j-2, 3j-1, 3j] \coloneqq 0$.

In block 3 the variable j is set to 1. This means that the calculation starts from the first bit.

In block 4 the ADC reads i-th signal, which is assigned to the variable X.

In block 5 the j-th bit of the variable X is compared with the value of the variable $A[j]$.

If the bits do not match, go to block 6. If these bits match, then go to block 15, where 1 is added to the value of the array $D[j]$, which means one more identical bit in the j-th bit. Then to block 16, where the end of the check is checked, i.e., $i = N$? If the end of the check, go to block 6, otherwise go to block 10.

Block 6 checks the value of the variable $A[j]$. If this value is equal to '1', go to block 7, otherwise go to block 8.

Going to block 7 means that a complete "cycle" has been completed, i.e., there has been a transition from '0' to '1' and from '1' to '0' for j-th bit. Therefore, one is added to the value of the variable $F_q[j]$: $F_q[j] \coloneqq F_q[j] + 1$. Also, $D[j]$is added to the value of the variable $N_{1q}[j]$:

$N_{1q}[j]$:= $N_{1q}[j]$+ $D[j]$. Then the transition to block 9 is carried out. In block 8, $D[j]$the value of the variable $N_{0q}[j]$: $N_{0q}[j]$:= $N_{0q}[j]$+ $D[j]$. Then the transition to block 9 is carried out. In block 9 the value of the variable $A[j]$ is inverted: $A[j] \coloneqq \overline{A[j]}$, i.e., if the variable value $A[j]$ was equal to '0', it becomes '1', or vice versa, if $A[j]$ was '1', it becomes '0'. In this block the variable $D[j]$ is assigned a 1. Then the transition to block 10 is made. In block 10 the value of the variable j is incremented by one, and go to block 11. In block 11 the value of the variable j is compared with the number M. If $j > M$, it means that all bits were checked and the transition to block 12 is carried out, otherwise the go to block 5.

In block 12 the value of the variable i is incremented by one and the transition to block 13 is carried out. In block 13 the value of the variable i is compared with the number N. If $i > N$, it means that the required number of signals from the ADC was read and the transition is made to block 14, otherwise go to block 3.

In block 14 the process of calculating the informative attributes for each of j-th bit and writing them in their respective places in the array Z takes place: $Z[3j-2] \coloneqq f_{q,}$ $Z[3j-1] \coloneqq N_{1q_j}/N_{0q_j}$, $Z[3j] \coloneqq N_{1q_j}/N$; $j = 1 \div$ M. And the process of calculating the informative attributes comes to an end.

Dynamics of accident development. To determine the dynamics of the accident development it is necessary to calculate the parameters f_{q_j}, k_{q_j}, K_{3q_j} of PBS and follow the change of parameters in time cyclically over a certain period of time. However, this approach for an operating unit requires more time to determine the pattern of parameter changes. In such cases the defect simulation technology comes to the rescue. Below we propose the technology of defect simulation, the essence of which is to add various random noise to the force signal corresponding to the normal mode of operation of SRPU and processing signals with the noise caused by supposed changes in the technical condition.

The validity of the proposed defect simulation technique is illustrated by the example of the following computational experiment.

To conduct the experiment, we:

1. selected filtered signal $U(i\Delta t)$ of change of force of rods on suspension for one period of the walking beam-pumping unit Fig. 4a.

2. created artificially a random signal (random) $\varepsilon(i\Delta t)$ of a certain amplitude and frequency. Fig. 4b.

3. generated a total noisy signal d $g(i\Delta t) = U(i\Delta t) + \varepsilon(i\Delta t)$ (Fig. 4c.).

4. performed the algorithm for calculating the parameters: f_{q_j},k_{q_j}, K_{3q_j} of PBS both for the filtered signal $U(i\Delta t)$ and for the noisy signal $g(i\Delta t)$.

5. repeating points 2 and 3 for different amplitudes and frequencies of the random signal (random) $\varepsilon(i\Delta t)$, calculated the parameters: f_{q_j},k_{q_j}, K_{3q_j} of PBS for the obtained noisy signals $g_m(i\Delta t)$.

Thus, the pattern of influence of amplitude and frequency of the random signal $\varepsilon(i\Delta t)$on the change of values of the parameters: f_{q_j},k_{q_j}, K_{3q_j} of PBS.

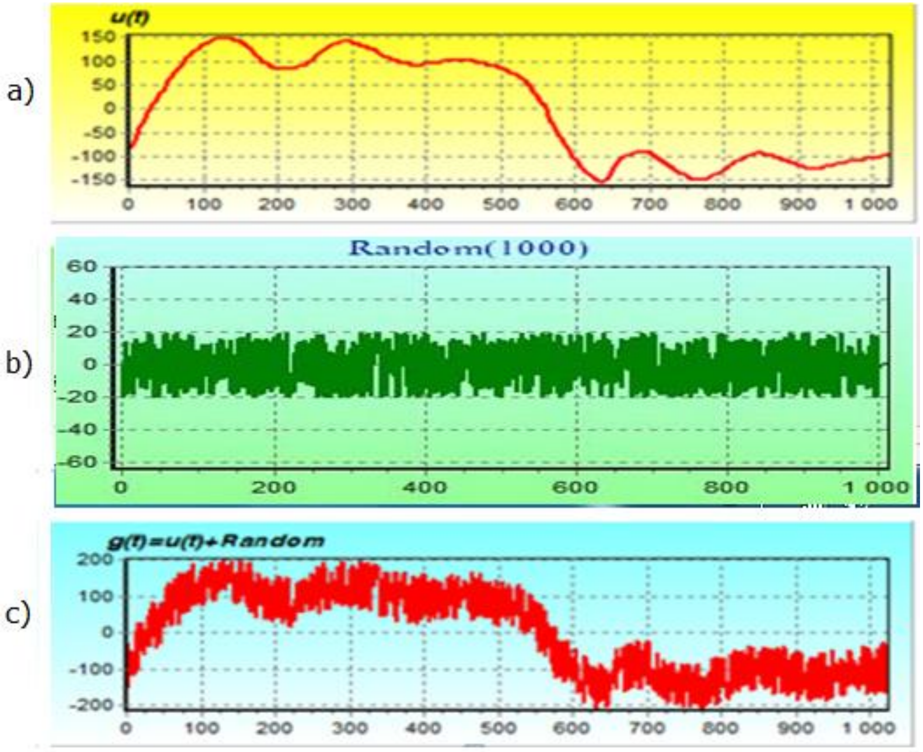

Fig. 4. Signals of the experiment: a) signal $U(i\Delta t)$ of change of the force for the period of the walking beam-pumping unit; b) artificially created random signal (random) $\varepsilon(i\Delta t)$; c) total noisy signal $g(i\Delta t) = U(i\Delta t) + \varepsilon(i\Delta t)$.

4. Conclusion

1. The constructed algorithm for calculating the estimates of informative attributes of a signal based on positional-binary components in an array allows assessing the history of object's condition, using archive files of dynamometer charts.

2. The algorithm for calculating the estimates of informative attributes of the signal in the course of measurement and analog-to-digital conversion without saving the array allows carrying out in a certain time interval operational control of changes in the technical condition directly at the well, without transmitting information to the control station.

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