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## **Digital Processing of Frequency–Pulse Signal in Measurement System**

**D. Świsulski, E. Pawłowski and M. Dorozhovets**

**Abstract** The work presents the issue of the use of multichannel measurement systems of sensors processing input value to impulse signal frequency. The frequency impulse signal obtained from such sensors is often required to be processed at the same time with a voltage signal which is obtained from other sensors used in the same measurement system. In such case, it is usually necessary to sample the output signals from all sensors in the same, predetermined points in time. Sampling voltage signal by means of A/D converters is practically possible in any selected time points, and the sampling frequency–pulse signal FPS requires special algorithms. The authors present the algorithms of digital signal processing pulse frequency offline and online modes, providing the acquisition of samples at certain evenly distributed points over time.

**Keywords** Multi-channel measurements system • Converter with frequency output • Frequency-pulse signal • Analog-to-digital conversion • Instantaneous frequency • Signal reconstruction

# 1 Introduction

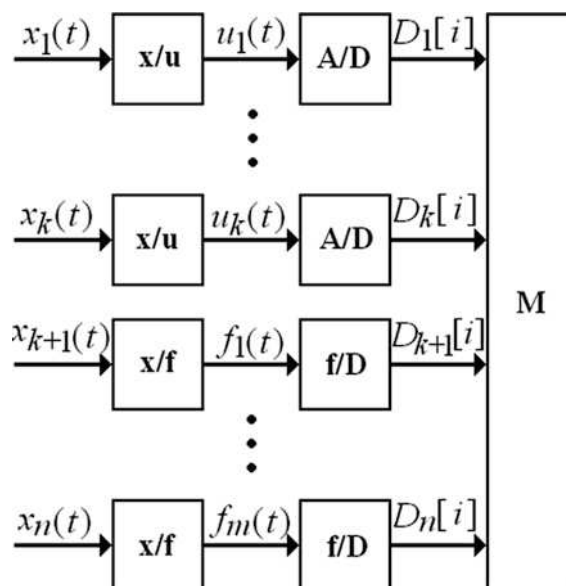
Modern measurement systems use various digital signal processing algorithms. For this purpose, all the measured values of the input system must be converted to their digital representations by suitable sensors and A/D converters, for which the most commonly used is an indirect voltage signal. This is due to the fact that now commonly available are integrated A/D converters processing only analogue voltage signal.

Often used instead of the voltage signal is the frequency signal [1, 2], which is easily and accurately processed into the digital form by means of metering systems and has a high resistance to interference, which greatly facilitates the transmission over long distances. The frequency signal can be obtained using integrated voltage-to-frequency converters VFC [3] or using sensors with frequency output [4, 5]. In multichannel measurement systems, both types of signals are often used simultaneously: voltage and frequency [6]. The structure of the measurement system under consideration is shown in Fig. 1.

During the acquisition of analogue signals  $x(t)$ , defined at any time in the time interval of observation, they are processed on the next channel on the  $N$  strings of numbers  $\{D_k[0], D_k[1], D_k[2], \dots, D_k[N-1]\}$ . They represent, respectively, the instantaneous values of analogue signals at regular intervals and are placed in the memory M of the measurement system. To maintain proper timing relationship between all the input quantities, analogue-to-digital processing in each channel should be carried out at the same time instants, typically evenly spaced in time, as required by DSP algorithms currently used (e.g. FFT, Hilbert transform, etc.).

If the signal is an intermediate voltage  $u(t)$  produced by sensor type  $x/u$ , then the processing to digital form is implemented as standard in the A/D converter, and the

**Fig. 1** Multichannel measuring system with tracks that use voltage signals  $u_1, \dots, u_k$  and frequency signal  $f_1, \dots, f_m$



moment sampling can be chosen almost arbitrarily. A significant problem occurs when the intermediate signal is a variable in time frequency  $f(t)$ , since the pulses of the output frequency signal of the sensor type  $x/f$  are generated with a different time interval. This time depends on the mean value of the input  $x(t)$  at the time of the previous pulse [7]. Therefore, to obtain the frequency signal, samples uniformly distributed at certain time instants require special methods other than voltage circuit.

## 2 Frequency–Pulse Signal

The sensor frequency output is a converter of the instant value of the measured quantity  $x(t)$  to the instantaneous value of the frequency  $f(t)$  with a coefficient of proportionality known as sensitivity of the sensor  $S$ :

$$f(t) = Sx(t). \quad (1)$$

The frequency  $f$  is a parameter of periodic signal  $y(t)$  present at the output of the sensor. In practice, it is usually a voltage signal, which may be of any shape: sinusoidal, triangular, rectangular, etc. [7]. In such case, the instantaneous values of the signal  $y(t)$  do not reflect the actual values of the measured value  $x(t)$ , but they are a particular form of a periodic-input function  $F(\varphi)$ , describing the shape of the signal  $y(t)$ . The argument of the function  $F(\varphi)$  is a variable during the phase  $\varphi(t)$  of the signal  $y(t)$ :

$$y(t) = F(\varphi(t)). \quad (2)$$

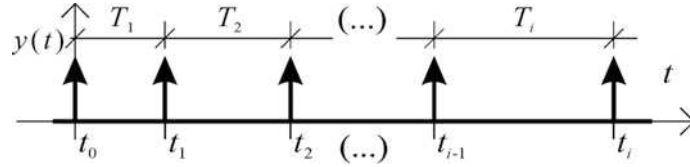
If the frequency of the output of the sensor is constant  $f = \text{const}$ , then the phase  $\varphi(t)$  of this signal is a linear function of time:

$$\varphi(t) = 2\pi ft + \theta, \quad (3)$$

where  $\theta$  is the initial phase. Otherwise, when the frequency  $f(t)$  of the signal changes, the phase signal  $\varphi(t)$  is described by an integral relationship:

$$\varphi(t) = 2\pi \int_0^t f(t) dt + \theta. \quad (4)$$

Regardless of the actual shape of the signal  $y(t)$  described by Eq. (2), in measuring systems, processing frequency to form a numerical includes only the selected characteristic of the states of this signal, usually timely rising or falling slope, which is marked by periods of the signal. Therefore, in practice, the signal  $y(t)$  can be considered as a series of pulses Dirac  $\delta$  shown in Fig. 2, appearing at moments  $t_i$  separated from each other by intervals  $T_i$ , corresponding to the following equal increments of the signal phase  $\Delta\varphi$  equal to the period of  $2\pi$ :



**Fig. 2** The idealised frequency-pulse signal

$$y(t) = \sum_{i=-\infty}^{+\infty} \delta(t - t_i), \quad t_i - t_{i-1} = T_i. \quad (5)$$

The signal  $y(t)$  shown in Fig. 2, described by the relation (5), whose instantaneous frequency  $f(t)$  is proportional to the value of the processed  $x(t)$  according to Eq. (1), will be called as the frequency-pulse signal FPS. The fundamental problem is to convert instantaneous frequency  $f(t)$  of the signal FPS  $y(t)$  (5) to its digital representation of  $D[i]$  (Fig. 1). In measurement technique, having respectively taken into account the transformed Eq. (4), the instantaneous frequency  $f(t)$  of the signal is determined by the derivative of the phase  $\varphi$  of this signal with respect to time  $t$  [8]:

$$f(t) = \frac{1}{2\pi} \frac{d\varphi}{dt}. \quad (6)$$

Phase  $\varphi(t)$  for a frequency-pulse signal FPS (5) is a continuous function of time, but the function  $F$  describing the shape of the signal  $y(t)$  (2) is not a one to one: different values of the phase  $\varphi(t)$  correspond to the same signal values  $y(t)$ . In the present signal, FPS (5) information is not accessible about the increase of the phase  $\varphi$  of the signal between the successive pulses. For such a signal, one cannot determine arbitrarily small increments of phase  $\varphi$ , and so one cannot also determine the frequency  $f$  on the basis of the derivative (6) for any time  $t$ . It is also clear that for the frequency-pulse signal FPS (5) we can determine only the increases of phase equal to a multiple of the period  $2\pi$ . So in order to determine the frequency  $f$  of the pulse signal (5) the derivative (6) should be replaced by the quotient of the growth of phase  $\Delta\varphi$  and time gain  $\Delta t$  [9]:

$$f(t) = \frac{1}{2\pi} \frac{\Delta\varphi}{\Delta t}. \quad (7)$$

Pulse at time  $t_i$  (rys. 2) is the incremental phase of the signal FPS (5) by an angle  $\Delta\varphi = 2\pi$  relative to the pulse at time  $t_{i-1}$ , in block  $f/D$  implementing sampling pulse frequency signal  $f(t)$  (Fig. 1); successive time intervals  $T_i$  are measured digitally via filling them with impulses  $T_{\text{ref}}$  of reference frequency  $f_{\text{ref}}$ , which allows to determine the next sampling frequency  $f_i$ :

$$f_i = \frac{1}{2\pi} \frac{\Delta\varphi}{\Delta t} = \frac{1}{2\pi} \frac{2\pi}{t_i - t_{i-1}} = \frac{1}{T_i} = \frac{1}{K_i T_{\text{ref}}} = \frac{f_{\text{ref}}}{K_i}, \quad (8)$$

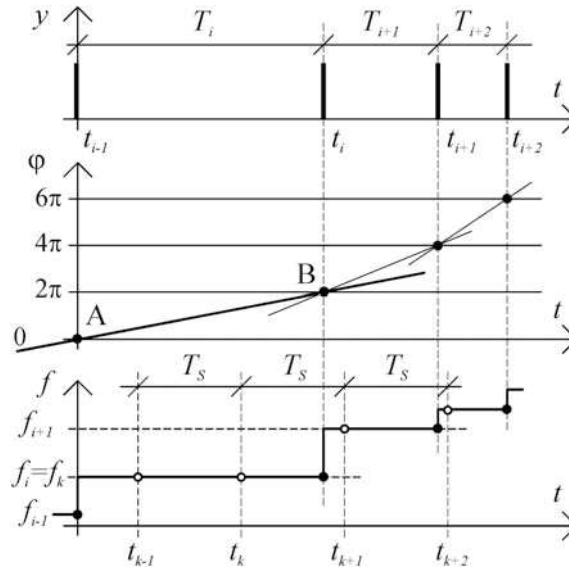
where  $K_i$  is the number of impulses of reference frequency  $f_{\text{ref}}$ , which have been counted in time  $T_i$ . The resultant quantization error can be analysed by simulation methods [9]. If the input value  $x(t)$  varies with time, the more frequencies  $f_i$  are obtained at times  $t_i$  and unevenly distributed over time (Fig. 2). Besides, the frequency value  $f_i$  is not an instantaneous value, being an average value for the time  $T_i$ , and therefore does not assign it to the time  $t_i$ , but properly chosen time  $t_i^*$  being within the interval  $T_i$  [9]. For an unknown form of  $x(t)$  it is not known where the moments of time  $t_i^*$  can be reasonably attributed to the value of  $f_i$ . Since the location of points  $(t_i^*, f_i)$  is not known, it is impossible unfortunately to approximate the value of  $f(t)$  for any time  $t$ . The frequency-pulse signal FPS has, however, the additional advantageous property: all the pulses occur exactly at those moments  $t_i$ , in which the phase angle of the signal growth  $\Delta\varphi = 2\pi$  is equal to the period of the signal  $y(t)$ . As a result, points  $(t_i, 2\pi i)$  allow clearly to approximate the course of the instantaneous phase  $\varphi(t)$  of the signal (5), and after calculation of the derivative (6) also the course of the instantaneous frequency  $f(t)$ .

The methods of processing a frequency-pulse signal FPS can be divided into two groups, depending on the position of the time for which the measurement result is determined. When measuring in offline mode, first time  $t_i$  of all pulses are remembered and then one determines the value measured in moments of measurement adopted by the position of the pulse of both preceding and occurring after the moment of the measurement. In online test, the measured value is determined only on the basis of the position of the pulse preceding the moment of measurement.

### 3 Offline Processing

While converting the frequency-pulse signal FPS in offline mode in M system memory (Fig. 1), the location of all subsequent pulses at times  $t_i$ , distant in time  $T_i$ , has been remembered, which allows approximating the course of instantaneous values of the phase  $\varphi(t)$  of the signal and after differentiation (6), reconstituting the instantaneous frequency  $f(t)$  [10]. For extremely low-frequency signals, it is often sufficient to assume that the frequency  $f(t)$  is constant in successive time intervals  $T_i$ ; according to the formula (3), the phase of the signal  $\varphi(t)$  can be interpolated in this range with a straight line. The procedure is shown in Fig. 3. Two points A and B define a straight line  $\varphi(t) = a_0 + a_1 t$  approximating phase of the signal in the time interval of  $(t_{i-1}, t_i)$ , in which the signal phase growth occurred  $\Delta\varphi = 2\pi$ . After simple transformations, we calculate  $a_0 = 0$  and  $a_1 = 2\pi/T_i$ , and taking into account (6) after setting the derivative we get  $f(t) = f_i = 1/T_i$  for  $t \in (t_{i-1}, t_i)$ . Following an analogous procedure to the next interval  $T_i$  we get a line approximating the course

**Fig. 3** The phase linear approximation of the frequency-pulse signal



of  $f(t)$  in accordance with accepted at the beginning of assumptions, which will determine the frequency  $f_k$  at times  $t_k = kT_S$  evenly distributed dug the period  $T_S$  of evenly sampling:

$$f_k = f(t_k) = f(kT_S) = 1/T_i, \quad t_k \in (t_{i-1}, t_i). \quad (9)$$

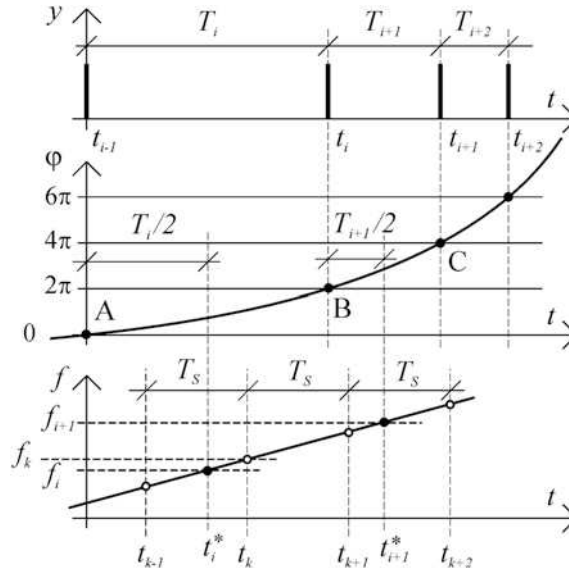
For signals changing faster, one can assume a linear change in frequency as a function of  $f(t)$ , and then one should approximate the course of the signal phase with a polynomial of the second degree  $\varphi(t) = a_0 + a_1t + a_2t^2$ . This requires determination of the coordinates of three points A, B and C (Fig. 4) corresponding to the phase increments  $\varphi(t)$  of the signal by further multiple  $2\pi$  at times  $t_{i-1}, t_i, t_{i+1}$ . The three moments of time determine the position of three successive signal pulses  $y(t)$ , away from each other by times  $T_i$  and  $T_{i+1}$ .

Points  $(0, 0)$ ,  $(T_i, 2\pi)$  and  $(T_i + T_{i+1}, 4\pi)$  enable the arrangement of a system of three equations with three unknowns  $a_0, a_1$  and  $a_2$ . After solving this system of equations one receives dependency of the instantaneous phase value  $\varphi(t)$ , and after differentiation (6) we obtain the polynomial interpolating instantaneous frequency  $f(t)$  (1) of the signal  $y(t)$  in the time interval of  $(t_{i-1}, t_{i+1})$ , based on the two neighbouring inter-pulse times  $T_i, T_{i+1}$ :

$$f(t) = \frac{1}{T_i + T_{i+1}} \left[ \frac{T_{i+1}}{T_i} - \frac{T_i}{T_{i+1}} + 2 + 2 \left( \frac{1}{T_{i+1}} - \frac{1}{T_i} \right) t \right]. \quad (10)$$

Substituting Eq. (10)  $f(t_i^* = 1/T_i)$  one can show that for the linear frequency change its mean value is equal to the instantaneous value of exactly half of the time

**Fig. 4** The second degree phase approximation of the frequency-pulse signal



interval  $T_i$ . Therefore, it is reasonable to interpolate in the time interval from the time  $t_i^* = t_{i-1} + T_i/2$  to time  $t_{i+1}^* = t_i + T_{i+1}/2$ , for which the instantaneous frequency takes appropriate values  $f_i = 1/T_i$  and  $f_{i+1} = 1/T_{i+1}$ . Following points  $t_i^*$ ,  $f_i$ :

$$t_i^* = t_{i-1} + T_i/2 = \sum_{j=1}^{i-1} T_j + T_i/2 \quad (11)$$

$$f_i = 1/T_i$$

mark the following sections of a broken line, which allows the download of frequency  $f_k$  at times  $t_k = kT_S$  equally distant in even time sampling period  $T_S$ :

$$f_k = f(t_k) = \frac{(t_k - t_i^*)f_{i+1} + (t_{i+1}^* - t_k)f_i}{t_{i+1}^* - t_i^*} \quad (12)$$

$$t_k = kT_S, \quad t_k \in (t_i^*, t_{i+1}^*).$$

In justified cases, one can also approximate the phase  $\varphi(t)$  of the pulse signal FPS with a higher order polynomial.

## 4 Online Processing

During online mode, to determine the value of the measured value at and time  $t_k$  on the basis of the pulse signal FPS, one can use only the position of the use preceding the moment  $t_k$ , which requires the use of extrapolation instead of interpolation used in offline mode. The easiest way of processing the pulse frequency signal lies in the fact that the value of the signal  $f_k = f_i$  at any time  $t_k$  is calculated (8) from the length of the last inter-pulse range  $T_i$  preceding time  $t_k$  (Fig. 5).

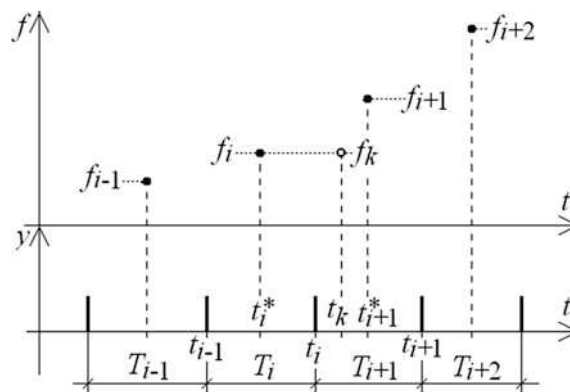
If the value of the processed signal  $x(t)$  changes during the measurement, it also changes the interval  $T_i$  between pulses FPS. Thus, for a longer period  $T_i$  of pulse signal FPS, the longer is the time between the time  $t_i^* = t_{i-1} + T_i/2$  which is assigned to the frequency  $f_i = 1/T_i$ , and time  $t_k$  for which one should extrapolate the values of the signal  $f_k$ . This means that the value obtained by extrapolating  $f_k$  may differ significantly from that which was actually sampled at the time  $t_k$ . In such case, the value of  $f_k$  at any time  $t_k$  can be calculated from the formula (13) using extrapolation of two adjacent inter-pulse ranges  $T_{i-1}$ ,  $T_i$  preceding the time  $t_k$ , assuming a linear variation in frequency and given that the frequency  $f_i$  resulting from the measurement interval  $T_i$  is equal to the instantaneous frequency at the middle point of the interval  $t_i^*$  (11) (Fig. 6):

$$f_k = f_{i-1} + \frac{(f_i - f_{i-1}) \left( t_k - \left( \sum_{j=1}^{i-2} T_j + \frac{1}{2} T_{i-1} \right) \right)}{\left( \sum_{j=1}^{i-1} T_j + \frac{1}{2} T_i \right) - \left( \sum_{j=1}^{i-2} T_j + \frac{1}{2} T_{i-1} \right)} \quad (13)$$

$$= \frac{1}{T_{i-1}} + \frac{2 \left( \frac{1}{T_i} - \frac{1}{T_{i-1}} \right) \left( t_k - \sum_{j=1}^{i-2} T_j - \frac{1}{2} T_{i-1} \right)}{T_{i-1} + T_i}.$$

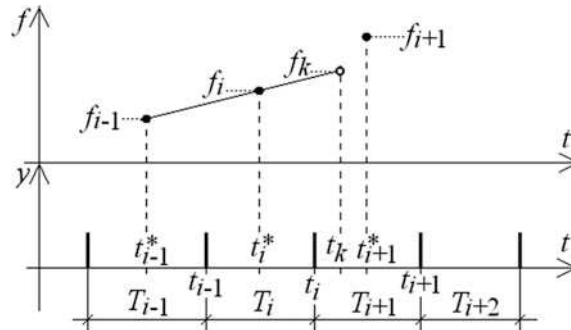
The frequency determined on the basis of the last two periods may differ materially from its current value. Figure 7 shows the error distribution of the

**Fig. 5** Online frequency determination in interval between the last inter-pulse range

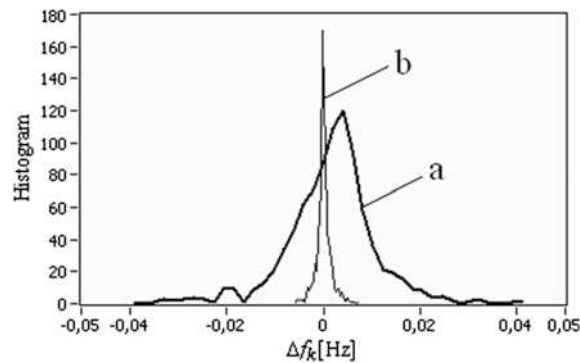




**Fig. 6** Online frequency extrapolation of the last two inter-pulse ranges  $T_{i-1}$  and  $T_i$



**Fig. 7** Histograms of errors  $\Delta f_k$  for  $f_0 = 20$  Hz,  $a = 2$  Hz/s,  $s_{\max} = 0.001$  Hz and  $T_S = 100$  ms; **a** frequency determination from last period, **b** frequency determination from two last periods



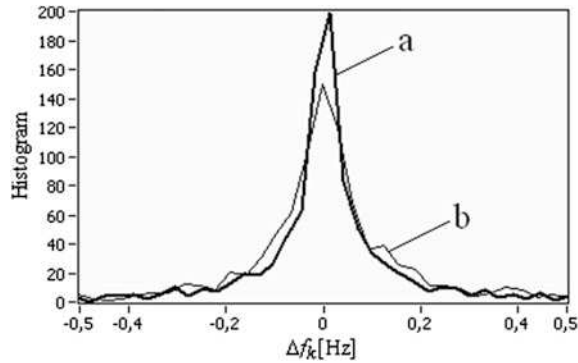
measured frequency, assuming a linear change of frequency  $f = f_0 + a \cdot t + s$  for  $f_0 = 20$  Hz,  $a = 2$  Hz/s,  $s_{\max} = 0.001$  Hz and the even sampling period  $T_S = 100$  ms, where  $s$  is the noise ( $s$  simulates the noise of the measured signal, but also processing errors). Error values were calculated as the difference between the frequency  $f'_k$  obtained from the measurement and value  $f_k$  accepted as true at the time  $t_k$ :  $\Delta f_k = f'_k - f_k$ .

If the noise level will be greater, errors measured using an extrapolation based on the last two periods may be even greater than a single measurement period. As an example, Fig. 8 shows the distributions of errors obtained for the same parameters as in Fig. 7, but with a noise value of  $s_{\max} = 0.1$  Hz.

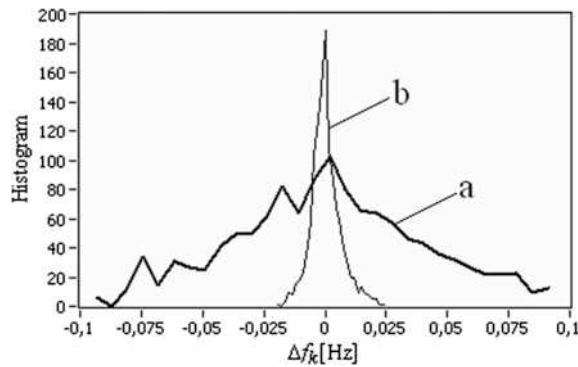
A similar analysis as for the linear frequency changes can be made to change the sine. Assuming that during measurement of the measured quantity changes as a function of time in a sinusoidal manner with frequency  $f_s$ , with the superimposed noise  $s$ :

$$f(t) = f_0 + f_m \cdot \sin(2\pi f_s t) + s, \quad (14)$$

**Fig. 8** Histograms of errors  $\Delta f_k$  for  $f_0 = 20$  Hz,  $a = 2$  Hz/s,  $s_{\max} = 0.1$  Hz and  $T_S = 100$  ms; **a** frequency determination from last period, **b** frequency determination from two last periods



**Fig. 9** Histograms of errors  $\Delta f_k$  distribution for  $f_0 = 20$  Hz,  $f_m = 2$  Hz,  $f_s = 0.3$  Hz,  $s_{\max} = 0.001$  Hz and  $T_S = 20$  ms; **a** frequency determination from last period, **b** frequency determination from two last periods



where

$f_0$  the constant pulse signal frequency  $f(t)$  and  
 $f_m$  amplitude changes in the frequency of the pulse signal  $f(t)$ .

Figure 9 shows a distribution of errors with the sinusoidal pulse signal frequency change for  $f_0 = 20$  Hz,  $f_m = 2$  Hz,  $f_s = 0.3$  Hz,  $s_{\max} = 0.001$  Hz and an even sampling period of  $T_S = 20$  ms.

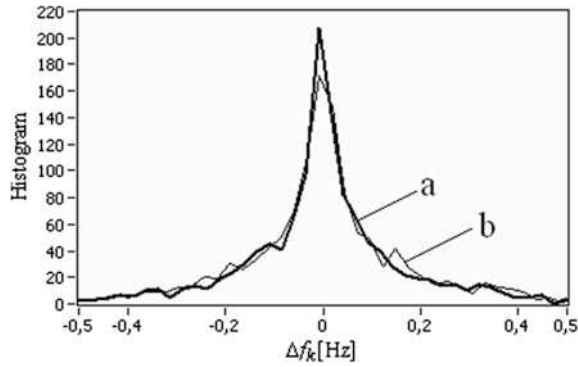
Figure 10 shows the error distribution obtained for the same parameters as in Fig. 9, but for  $s_{\max} = 0.1$  Hz.

The frequency  $f_k$  determined based on the last two ranges  $T_{i-1}, T_i$  (13) may also differ significantly from its current level if it does not vary in a manner similar to a linear, but in a random manner. In such case, a more favourable method may be the one in which another earlier interval  $T_{i-2}$  is used. The additional frequency  $f_{i-2}$  is used to determine the difference (see Figs. 11 and 12):

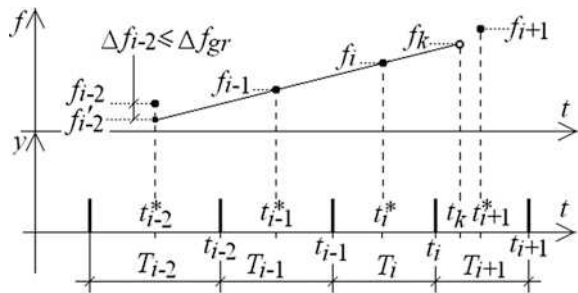
$$\Delta f_{i-2} = |f_{i-2} - f'_{i-2}|, \quad (15)$$



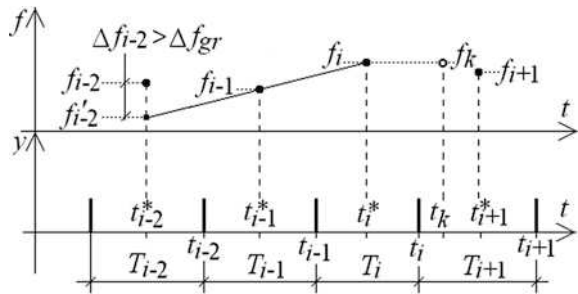
**Fig. 10** Histograms of errors  $\Delta f_k$  distribution for  $f_0 = 20$  Hz,  $f_m = 2$  Hz,  $f_s = 0.3$  Hz,  $s_{\max} = 0.1$  Hz and  $T_S = 20$  ms; **a** frequency determination from last period, **b** frequency determination from two last periods



**Fig. 11** Online frequency determination of the last three ranges for  $\Delta f_{i-2} \leq \Delta f_{gr}$



**Fig. 12** Online frequency determination of the last three ranges for  $\Delta f_{i-2} > \Delta f_{gr}$



where

- $f_{i-2}$  frequency value determined from the interval  $T_{i-2}$ ,
- $f'_{i-2}$  frequency value in the middle of the range of  $T_{i-2}$  determined by extrapolation of the ranges  $T_{i-1}$  and  $T_i$ .

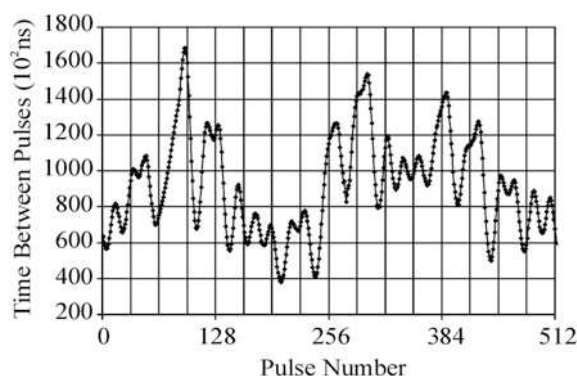
Obtained from the formula (15) value  $\Delta f_{i-2}$  is compared with the established experimentally limit value  $\Delta f_{gr}$ . For  $\Delta f_{i-2} \leq \Delta f_{gr}$  as a result of the measurement is taken the frequency  $f_k$  determined by extrapolation of the intervals  $T_{i-1}$  and  $T_i$  (Fig. 11). If  $\Delta f_{i-2} > \Delta f_{gr}$  as a result of the measurement, the frequency  $f_i$  value is assumed to be determined from the interval  $T_i$  (Fig. 12).

For the conditions shown in Figs. 7, 8, 9 and 10 measurement simulations were repeated. For the proposed method, the error distributions were obtained corresponding to the distribution b in Figs. 7 and 9 and a distribution similar to that in Figs. 8 and 10. This confirms the validity of the adopted considerations. For the measured signal with a small change dynamics and low noise, frequency is determined by extrapolating on the basis of the last two periods. With high content of noise frequency, value is determined from the last period. The simulations performed adopted experimentally determined limit value of  $\Delta f_{gr}/f_{i-2} = 0.2\%$ . It has been obtained by determining the error values as a function of limit value.

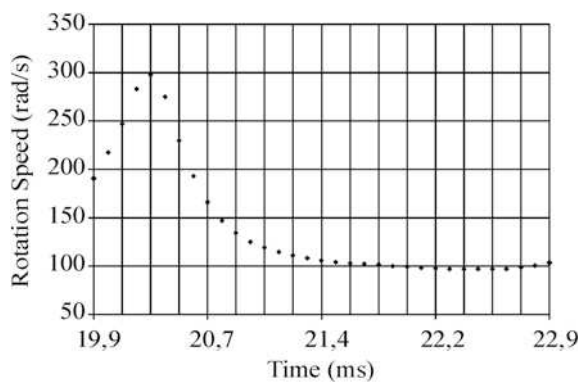
## 5 Practical Application

For the practical verification of the algorithms, combined were the single-phase electric motor of low power with incremental rotary pulse encoder generating 512 pulses per revolution of the shaft. For measuring and recording the times  $T_i$  a measuring card was used (CTM-PER, company KEITHLEY) co-working with an IBM PC class computer. The measuring card has a 28-bit counter that counts the reference signal of 10 MHz, the FIFO memory provides meter reading “on the fly”, and for measuring the next time  $T_i$  in the range from 0.1 ms to 26.8 s and a transfer of results into the computer memory. Figure 13 shows the value of 512 times  $T_i$  recorded in one revolution of the motor shaft, which is then converted to the rotation speed and assigned in accordance with (11) times  $t_i^*$  lying in the middle of  $T_i$  giving a sample distributed unevenly over time. For greater clarity, Fig. 14 only shows the position of the selected part of pulses for  $i = 234, \dots, 268$ , covering part of the graph in Fig. 13 for the times  $t_i = 19.9, \dots, 22.9$  ms. The total measurement time was 47.3 ms (one full rotation of the motor shaft). Uniform sampling period  $T_s = 92.6$  ms (sampling rate approx. 10,800 samples/s) was adopted in such a way, so as to obtain the same number of 512 samples. Using the algorithm for offline (12) 512 signal values were calculated at times  $t_k = kT_s$  evenly distributed over time

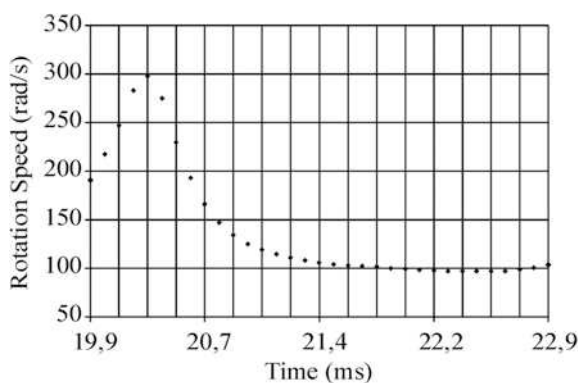
**Fig. 13** Intervals  $T_i$  for one revolution of the motor shaft



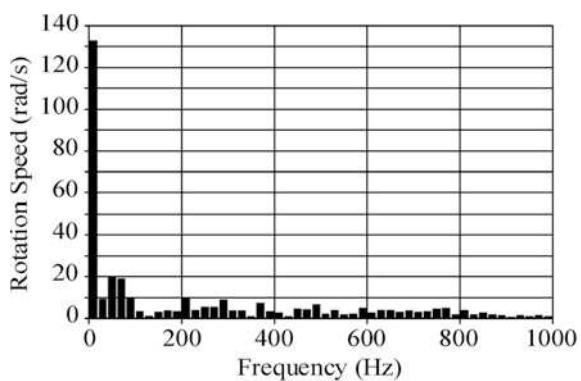
**Fig. 14** Rotation speed unevenly sampled converted from a pulse scale into a timescale (pulse from 234 to 268 in Fig. 13)



**Fig. 15** Rotation speed evenly sampled converted from Fig. 14 using offline mode method (12)



**Fig. 16** Frequency spectrum speed calculated for one rotation of the motor shaft after the application of a uniform sampling FPS



(Fig. 15), and then set a frequency spectrum signal speed of the motor shaft (Fig. 16) with a visible component of a constant value of 133 rad/s and a 50 Hz component of the value of 20 rad/s.



## 6 Conclusions

The presented review of the methods of acquisition of the pulse signal at specific sampling instants shows that the choice of method depends on the measurement mode (online or offline) and on the nature of the change of the measured value. The simplest solution is to determine the value measured on the basis of a single inter-pulse interval, more complex methods using two or more time intervals. The presented methods allow to obtain information on the measured value at the same time for the voltage and frequency of the channel, and the samples obtained from the frequency channels can be processed by methods requiring a constant sampling frequency (e.g. The FFT, Hilbert transform). An additional advantage is the possibility to determine the resolution in the same way for both types of channels, using the effective number of bits.

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