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Problems with microprocessor voltage-to-frequency and frequency-to-voltage converters implementation

***Abstract**. The article presents the problems of digital voltage-to-frequency and frequency-to-voltage processing. Transducer systems implemented in microprocessor technology are presented, the timing of signals and functioning algorithms are discussed. An analysis of processing errors has been performed and the results of experimental studies of realized systems are presented.*

***Streszczenie.** W artykule zaprezentowano problematykę cyfrowego przetwarzania napięcie-częstotliwość oraz częstotliwość-napięcie. Przedstawiono układy przetworników zrealizowanych w technice mikroprocesorowej, omówiono przebiegi czasowe sygnałów i algorytmy działania. Dokonano analizy błędów przetwarzania oraz zaprezentowano wyniki badań eksperymentalnych zrealizowanych układów. (**Mikroprocesorowe przetworniki napięcie-częstotliwość i częstotliwość-napięcie**).*

Keywords: Voltage-to-Frequency Converter, Frequency-to-Voltage Converter, pulse frequency modulation.
Słowa kluczowe: przetwornik napięcie-częstotliwość, przetwornik częstotliwość-napięcie, modulacja częstotliwości impulsów.

Introduction

In any measurement system it is necessary to apply the appropriate sensors that convert all physical input quantities to a different quantity, which then undergoes a process of sampling, quantization and coding into a digital form [1]. For this purpose, modern measuring systems most commonly use a voltage signal due to the wide availability of many types of integrated analog-to-digital converter circuits. In some applications it is also advantageous to use the frequency signal FS for this purpose, which can be digitized in a simple manner by means of counters to process with high precision [2]. The advantages of frequency signal may also include its high resistance to interference, ease of transmission over long distances without loss of information and the availability of patterns in the highest world standards accuracies [1]. For these reasons, the voltage-frequency, frequency-to-voltage and frequency-code processing is often used [3, 4, 5]. The article presents microprocessor-based circuits performing this kind of processing.

The measuring system with frequency data carrier

In the measuring system with frequency data carrier the input variable x is processed in the sensor to frequency f proportional to it [2]:

$$f(t) = S\ x(t) \tag{1}$$

where: S – sensor sensitivity.

In most current sensors, the frequency output SFO of the output signal $y(t)$ has a form of series of impulses:

$$y(t) = \sum_{i=-\infty}^{\infty} p(t - t_i) \tag{2}$$

where: $p(t)$ – function describing the shape of a single pulse.

For the pulse signal of the form (2) one can not specify the frequency f (1) for any time t, due to the step increase in the phase of the signal by value 2π at times t_i of the occurrence of the following impulses [6]. For such a signal, each two adjacent impulses at times t_{i-1}, t_i a distant from one another by the time inverse proportional to the average value $\bar{x}$ of the input signal [3]:

$$\frac{1}{t_i - t_{i-1}} = S\ \bar{x}(t_{i-1}\ , t_i) \tag{3}$$

where: $\bar{x}(t_{i-1}, t_i)$ - the average value of the input signal x in time span from t_{i-1} to t_i.

In analog sensors SFO the frequency relationship (3) is carried out by an combining integrator of the input signal x and a comparator implementing the uniform quantization of the integrals obtained from the quantization step equal to the inverse of the sensitivity of the sensor S [6]:

$$\int_{t_{i-1}}^{t_i} x(t)dt = \frac{1}{S} \tag{4}$$

The impulses of the output signal (2) appear at the output of the sensor always at times t_i, at which the value of the integral (4) reaches the next threshold of quantization. In microprocessor transducers the relations (3) is implemented by special software.

Microprocessor voltage-to-frequency converter

The construction and operation of the microprocessor voltage-to-frequency converter [3] shown in the block diagram (Fig. 1) and on the time course of signals (Fig. 2).

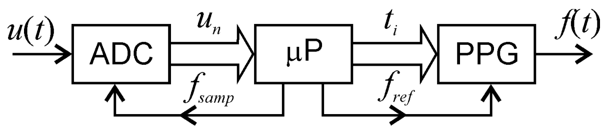

Fig. 1. Block diagram of the voltage-to-frequency converter

The analog-digital converter samples at times t_n the input voltage $u(t)$ with a sampling frequency f_{samp}, then quantizes and encodes them to digital form u_n, based on which the microprocessor μP calculates moments t_i (3). The programmable pulse generator (PPG) generates output impulses at times t_i, suitably programmed by microprocessor and counting impulses of the reference frequency f_{ref}. The block diagram of the algorithm executed by a microprocessor is shown in Figure 3. Each time after receipt at t_n of the voltage sample u_n it is checked whether the designated time t_i generating the next output impulse is earlier than the time $t_n + T_{sampl}$ of the next sample of the input voltage. If the condition is satisfied than the microprocessor programs the PPG generator and an impulse is generated, otherwise another input voltage sample is collected and the calculation process is repeated.

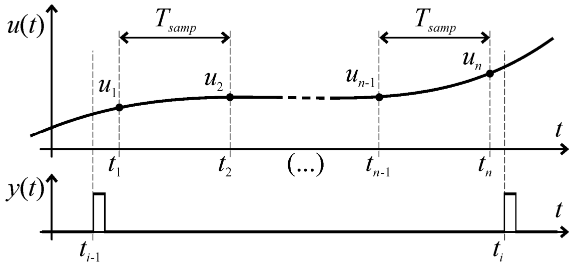

Fig. 2. Timing of passes of the voltage-to-frequency converter

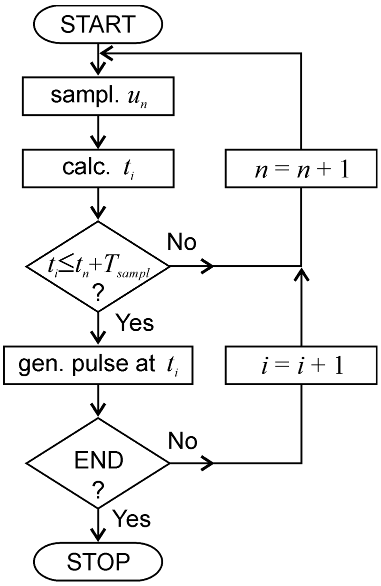

Fig. 3. Voltage-to-frequency coverter algorithm

There are several ways to calculate the time t_i (3) of generating the output pulse [3]. For low-frequency signals calculations can be performed on the basis of only one last voltage sample u_n:

$$t_i = t_{i-1} + \frac{1}{S \cdot u_n} \tag{5}$$

Taking into account the two voltage samples: u_{n-1} and u_n, the impulse position t_i can be determined as a solution to a quadratic equation:

$$t_i = \frac{-2S\left(u_{n-1}t_n - u_n t_{n-1}\right) + \sqrt{\Delta}}{2S\left(u_n - u_{n-1}\right)} \tag{6}$$

where:

$$\begin{aligned}\Delta = {} & 4S^2\left(u_{n-1}t_n - u_n t_{n-1}\right)^2 + \\ & + 8S^2 t_{i-1}\left(u_n - u_{n-1}\right)\left(u_{n-1}t_n - u_n t_{n-1}\right) + \\ & + 4S^2 t_{i-1}^2\left(u_n - u_{n-1}\right)^2 + 8S\left(u_n - u_{n-1}\right)\left(t_n - t_{n-1}\right)\end{aligned} \tag{7}$$

Taking into account all n of samples u_1 ... u_n collected between times t_{i-1} ... t_i calculations are performer by approximate solution of equation (3), after replacing the integral (4) by the sum-up operation:

$$t_i = t_{i-1} + \frac{n}{S \cdot \sum_{k=1}^{n} u_k} \tag{8}$$

In order to compare the reported methods of implementation of the calculation is assumed, that on the input of the converter the voltage $u(t)$ sinusoidally variable with a frequency f_s, the constant component U_0 and amplitude U_m was given:

$$u(t) = U_0 + U_m \sin\left(2\pi\ f_s\ t\right) \tag{9}$$

and then calculated the average relative error:

$$\delta = \frac{\bar{u} - \bar{u}_s}{\bar{u}_s} \tag{10}$$

where $\bar{u}$ is the mean value of the input voltage $u(t)$ in the time interval from t_{i-1} to t_i calculated on the basis of the transformed according to (3):

$$\bar{u} = \frac{1}{S\left(t_i - t_{i-1}\right)} \tag{11}$$

and $\bar{u}_s$ is the mean value the signal calculated precisely:

$$\bar{u}_s = \frac{1}{t_i - t_{i-1}} \int_{t_{i-1}}^{t_i} \left(U_0 + U_m \sin\left(2\pi\ f_s\ t\right)\right) \tag{12}$$

Figure 4 shows the maximum error value calculated according to (10) for: U_0 = 30 V, U_m = 10 V and S = 0,0025 Hz/V for different values of the f_s/f_{samp} ratio while for the method using two samples according to (6) the dependence is quadratic (line b) and for other methods (5) and (8) – linear (lines a and c). For small values of the ratio f_s/f_{samp} the smallest errors guaranteed method using two samples (b), for the larger relationship the method of calculation of n samples (c) is better. The most significant errors gives a method of calculation from one sample (a), but it is the simplest computationally and is therefore the fastest.

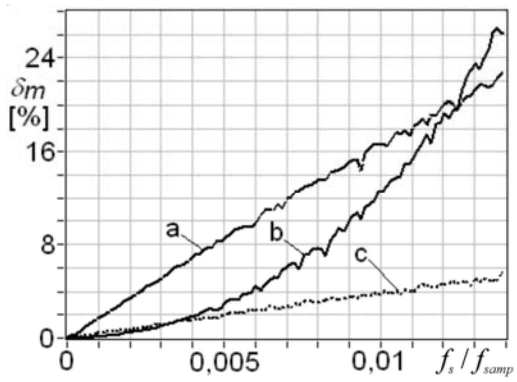

Fig. 4. Maximum converter errors δ_m vs. signal frequency to sampling frequency ratio for sinusoidal input voltage, for U_0 = 30 V, U_m = 10 V, S = 0,0025 Hz/V; pulse instant calculated from: a – last voltage sample (5), b – two last voltage samples (6), c – mean value of voltage samples after last pulse (8)

Also important is the error dependency δ_m of the sensitivity S shown in Figure 5. Methods utilizing one (a) or two (b) samples show large errors for small values of sensitivity S, because then the time intervals between impulses t_{i-1}, t_i are larger and changes in input voltage $u(t)$ may differ significantly from the assumed linear change. From this point of view, the method using the average value of n samples (c) is better, is limited by the value of the sensitivity S:

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$$S < \frac{f_{samp}}{2\,U_{\max}} \tag{13}$$

where $U_{\max}$ – the maximum input voltage.

Above value S the number of samples between adjacent impulses is less than two, which causes the error δ_m to grow strongly.

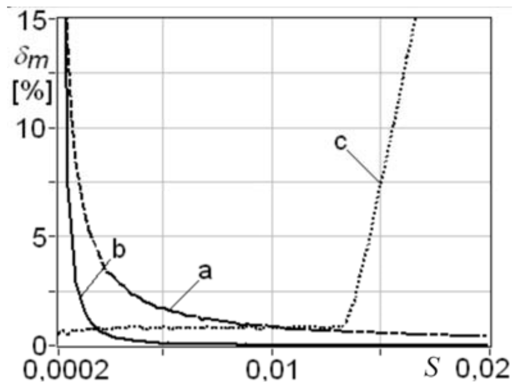

Fig. 5. Maximum converter errors δ_m vs. S for sinusoidal input voltage, for U_0 = 30 V, U_m = 10 V, f_s = 0,002 f_{samp}; pulse instant calculated from: a – last voltage sample (5), b – two last voltage samples (6), c – mean value of voltage samples after last pulse (8)

Microprocessor frequency-to-voltage converter

Frequency-to-voltage converters are used when it is necessary to integrate sensors with frequency output in a measurement system that uses a voltage analog-to-digital ADC [7] or when it is necessary to appoint timing between signals represented voltage and frequency [8]. The construction and operation of microprocessor frequency-to-voltage converter is shown in the block diagram (Fig. 6).

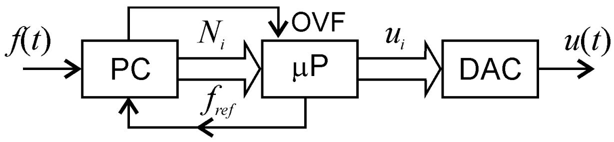

Fig. 6. Frequency-to-voltage converter block diagram

Microprocessor μP reads the pulse counter cyclically PC and based on the read pulse number N_i, the number of K overflows OVF and standard frequency f_{ref} calculates the input frequency f and converts it according to the assumed processing functions to u_i voltage and sends it to a digital-analog converter DAC. On the DAC output, the achieved output voltage is $u(t)$. The measurement of the input frequency $f(t)$ can be implemented in two ways as shown in Figure 7. In the first method (Fig. 7a) the capacity of the PC counter of $N_{\max}$ impulses is counted in a continuous pulses at a reference frequency f_{ref}. At times t_i the occurrence of pulses of the input signal $y(t)$ with a frequency $f(t)$ of the meter is read on the fly and the actual content of N_i and the number of overflows K of the time t_{i-1} of the previous impulse is used to calculate the time between the impulses of T_i and frequency f_i:

$$f_i = \frac{1}{T_i} = \frac{f_{ref}}{N_i - N_{i-1} + K\,N_{\max}} \tag{14}$$

In the second method (Fig. 7b) the PC counter counts the continuous impulses of the input signal $y(t)$ with a frequency $f(t)$ and is read on the fly at times t_i of the occurrence of impulses of the reference frequency f_{ref} and a period of T_{ref}. Microprocessor μP based on meter readings states of N_i and the number of its overflow K calculates the frequency:

$$f_i = \frac{N_i - N_{i-1} + K\,N_{\max}}{T_{ref}} \tag{15}$$

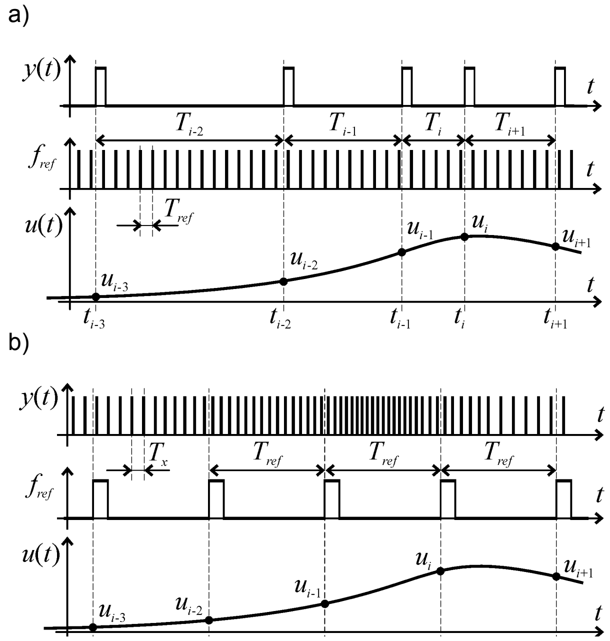

Fig. 7. Frequency-to-voltage converter timing of signals: a – measurement of the period, b – measurement of the frequency

In both methods, the calculated frequency f_i in moments t_i is converted to a voltage u_i taking into account the sensitivity of the sensor S and the initial frequency f_0:

$$u_i = S\left(f_i - f_0\right) \tag{16}$$

The start frequency f_0 allows for sensitivity S = 1 V/kHz to obtain bipolar processing characteristics -5 V ... +5 V (f_0 = 5 kHz) or the characteristics of the unipolar 0 ...+10 V (f_0 = 0). It is also possible to program another characteristic of the user's needs.

Transducer errors in a static state (f = const.) were determined experimentally stating its entry known frequency f_i and measuring the output voltage u_i. The transducer δu relative error was calculated according to the formula:

$$\delta u = \frac{u_i - S\left(f_i - f_0\right)}{S\,f_{\max}} \tag{17}$$

where:

u_i - the voltage measured at the output of the DAC,
f_i – the frequency given at the input of the transducer,
$f_{\max}$ – maximum frequency, transducer range.

Figure 8 shows errors in static transducer for measuring frequency f_i according to the equation (15), T_{ref} = 100 ms (line a) and T_{ref} =1 s (line b), and for measuring the period T_i according to the equation (14) for f_{ref} = 16 MHz. It should be noted, that the error calculated according to the equation (17) contains the sum of all errors occurring in the transmitter: quantization error frequency measurement, calibration frequency error, DAC quantization error, DAC nonlinearity errors and rounding errors introduced by the calculation algorithm. The accuracy of the sensor can be improved by using modified frequency measurement algorithm [5].

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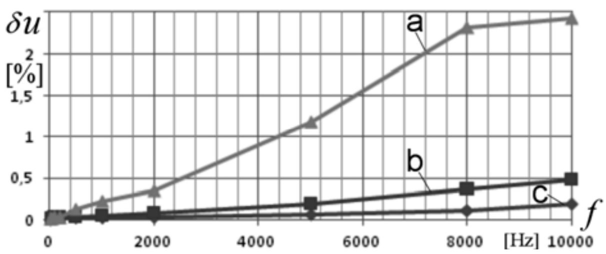

Fig. 8. The relative error for frequency-voltage converter in a static state: a – frequency measurement (15) for T_{ref} = 100 ms, frequency measurement (15) for T_{ref} = 1 s, measurement period (14) for f_{ref} = 16 MHz

For evaluation of the transmitter in the dynamic state, a programmable DDS generator with frequency modulation is used [9]. On the input of the transducer the signal frequency-modulated pulse was given:

$$f(t) = F_0 + F_m \sin(2\pi\ f_s\ t) \tag{18}$$

where:

F_0 – the constant component frequency,
F_m –amplitude component of the frequency hopping,
f_s – modulation frequency of the processed signal.

Due to minor dynamic errors, the transducer worked in period measurement mode (14) [10]. The converter has been examined for bipolar characteristic of conversion (f_0 = 5 kHz) and for unipolar (f_0 = 0). Exemplary results of the measurements carried out are shown in Figure 9.

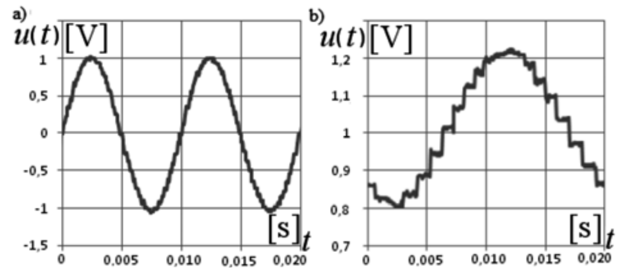

Fig. 9. Frequency-to-voltage converter output signal in a dynamic state: a – bipolar characteristic S = 1 V/kHz, f_0 = 5 kHz, F_0 = 5 kHz, F_m = 1 kHz, f_s = 100 Hz, b – unipolar characteristic S = 1 V/kHz, f_0 = 0, F_0 = 1 kHz, F_m = 200 Hz, f_s = 50 Hz

It should be noted, that the basic problem of digital processing in a frequency-to-voltage converter is obtaining results from measurements of frequency f_i at T = times t_i (Fig. 7), which is the average value of the frequency for the time t_{i-1} to t_i and should be assigned to a moment in time lying in the middle of this interval [10]. This is only possible in data processing systems in off-line mode [2]. In the digital frequency-to-voltage converters operating in on-line mode it is impossible to assign processing results to corresponding moments of time, as these results are received after the expiry of the time point to which they should be assigned. This results in impossible to avoid errors in position at the time of single samples. The second problem results from integrating the operation of the transducer with frequency output (4),whereby in the frequency-to-voltage converter the sampling frequency signal averaging is implemented, and not, as in other types of ADCs sampling of instantaneous values. Therefore, the unfavorable ratio of the processed signal frequency f_s to the frequency $f(t)$ of the impulse signal specified parameters F_0, F_m (18), the output frequency-to-voltage converter obtain a stepped line, the width of these "steps" is variable and dependent on the current value signal (Fig. 9b).

Summary

The article presents the methods and systems implemented in microprocessor technology for processing the voltage-to-frequency and frequency-to-voltage converters. The advantage of the proposed solutions is the possibility of forming a broad range of processing characteristics by modifying the software, with the unchanging part of hardware drivers.

Presented error analysis allows the adjustment of the characteristics of transducers to the parameters of the processed signal and reducing the level of errors. This is important, because the impulse frequency signal has a number of advantages from the metrological point of view [2], at the same time, however, it has some limitations due mainly to the integrating algorithm voltage-to-frequency transformation. As a result, the frequency signal can only be sampled in average, and reconstruction of instantaneous values requires the application of appropriate additional algorithms [6, 11].

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