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FEATURES OF THE ANGULAR SPEED DYNAMIC MEASUREMENTS WITH THE USE OF AN ENCODER

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Abstract. *Based on the most significant features of the angular velocity dynamic measurements selected by the authors, the main phases of measuring information transformation were established, which allowed to obtain new mathematical models in the form of transformation function, equations for estimating quantization errors, analytical dependences for measuring range that are initial for modeling physical processes occurring in such digital measuring channels with microprocessor control. The process of converting an analog quantity into a binary code is analytically described, an equation for estimating the absolute and relative quantization error is obtained and a measurement range is established, which provides a normalized value of relative quantization error for angular velocity measuring channels with encoder. For the first time, the equation of sampling error was obtained, and it was proved that the limiting factor of the angular velocity measurements upper limit is not only the normalized value of quantization error, as previously thought, but also the value of sampling frequency f_D. Therefore, to expand the measurement range (by increasing the upper limit of measurement), it is proposed not only to increase the speed of analog-to-digital conversion hardware, but also to reduce the execution time of software drivers for transmitting measurement information to RAM of microprocessor system. For this purpose, the analytical dependences of estimating the upper limit of measurement based on the value of the sampling step for different modes of measurement information transmission are obtained. The practical implementation of the software mode measurement information transmission is characterized by a minimum of hardware costs and maximum execution time of the software driver, which explains its low speed, and therefore provides a minimum value of the upper limit measurement. In the interrupt mode, the upper limit value of the angular velocity measurement is higher than in the program mode due to the reduction of the software driver's execution time (t_{FI} = 0). The maximum value of the angular velocity measurements upper limit can be achieved using the measurement information transmission in the mode of direct access to memory (DMA) by providing maximum speed in this mode (t_{FI} = 0, t_{DR} = 0). In addition, the application of the results obtained in the work allows at the design stage (during physical and mathematical modeling) to assess the basic metrological characteristics of the measuring channel, aimed at reducing the development time and debugging of hardware, software, and standardization of their metrological characteristics.*

Keywords: angular velocity, encoder, quantization, sampling, angular velocity measuring channel, transformation function

CECHY POMIARÓW DYNAMICZNYCH PRĘDKOŚCI KĄTOWEJ Z WYKORZYSTANIEM ENKODERA

Streszczenie. *Na podstawie najistotniejszych cech dynamicznych pomiarów prędkości kątowej ustalono główne fazy transformacji informacji pomiarowej, co pozwoliło na uzyskanie nowych modeli matematycznych w postaci funkcji transformacji, równań do szacowania błędów kwantyzacji, analitycznych zależności dla zakresu pomiarów, które są podstawą do modelowania procesów fizycznych zachodzących w takich cyfrowych kanałach pomiarowych ze sterowaniem mikroprocesorowym. analitycznie opisano proces konwersji wartości analogowej na kod binarny Po raz pierwszy otrzymano równanie błędu próbkowania i udowodniono, że czynnikiem ograniczającym górną granicę pomiarów prędkości kątowej jest nie tylko znormalizowana wartość błędu kwantyzacji, jak sądzono wcześniej, ale także wartość częstotliwości próbkowania f_D. Dlatego w celu rozszerzenia zakresu pomiarowego (poprzez zwiększenie górnej granicy pomiaru) proponuje się nie tylko zwiększenie szybkości działania sprzętu do konwersji analogowo-cyfrowej, ale również skrócenie czasu wykonania sterowników programowych do transmisji informacji pomiarowej do pamięci RAM systemu mikroprocesorowego. w tym celu uzyskano analityczne zależności górnej granicy pomiaru od wartości kroku próbkowania dla różnych trybów transmisji informacji pomiarowej. W trybie przerwania górna wartość graniczna pomiaru prędkości kątowej jest wyższa niż w trybie programu ze względu na skrócenie czasu wykonania sterownika programowego (t_{FI} = 0). Maksymalną wartość górnej granicy pomiaru prędkości kątowej można uzyskać przesyłając informacje pomiarowe w trybie bezpośredniego dostępu do pamięci (DMA) zapewniając maksymalną prędkość w tym trybie (t_{FI} = 0, t_{DR} = 0). Ponadto zastosowanie uzyskanych w pracy wyników pozwala na etapie projektowania (podczas modelowania fizycznego i matematycznego) na ocenę głównych cech metrologicznych kanału pomiarowego, co ma na celu skrócenie czasu rozwoju i debugowania sprzętu, oprogramowania oraz standaryzacji ich cech metrologicznych.*

Słowa kluczowe: prędkość kątowa, enkoder, kwantyzacja, próbkowanie, kanał pomiaru prędkości kątowej, funkcja konwersji

Introduction

During the rotation of a rigid body [1, 6] around its axis, the angle of rotation φ is a function of time

$$\varphi = f(t).$$

This equation is also called the equation of rotation, which is the basis for the experimental study of such parameters of rotational motion as angular velocity $\omega(t) = \frac{d\varphi}{dt}$, angular acceleration $\xi(t) = \frac{d\omega}{dt} = \frac{d^2\varphi}{dt^2}$ and dynamic moment $\mathrm{M}_D = J\frac{d\omega}{dt} = J\frac{d^2\varphi}{dt^2}$.

The vast majority of the rotational motion of mechanisms is described by the terms "angular velocity" or "frequency of rotation", the essence of which is different. We give the definition of these parameters of angular displacements corresponding to the international system of units of measurement [3].

Angular velocity is a physical quantity that is described by the first derivative of the angle of rotation φ for the time t, rad/s:

$$\omega(t) = \frac{d\varphi}{dt}.$$

Rotation frequency n is a physical quantity determined by the ratio of the number of revolutions N_O per rotation time, rpm:

$$n = \frac{N_O}{t}.$$

It is easy to see that the term "rotation speed n" used corresponds exactly to the physical quantity "rotation frequency". The basic equations for measuring rotation speed and rotation frequency are also the same.

The above also indicates that the speed, as well as the speed, are not synonymous with angular velocity. In physical terms, these are different physical quantities that are not proportional to each other. Equality

$$\omega = 2\pi n$$

valid only for uniform rotation.

Based on this, we note the first feature – the angular velocity is related to dynamic measurements, because at each time its instantaneous value is known, and the rotation frequency (rotation speed) to static, because the measurement result in this case characterizes the average speed per full revolution.

Angular velocity refers to non-electric quantities, which are measured by converting a non-electric quantity into an electric one using a primary measuring transducer (sensor). The presence of this measuring transformation determines the second feature of the measurement of angular velocity ω.

Encoders are now preferred for dynamic angular displacement transducers in dynamic angular velocity measurements. They perform the conversion of angular displacement into a sequence of electrical signals, the frequency of which contains information about the value and direction of the informative parameter.

Such transducers are used to measure angular velocity, speed and other physical quantities functionally related to it. The transformation equation for rotational motion sensors, which are based on the construction of angular displacement transducers – encoders, are shown in table 1.

Table 1. Transformation equation of angular displacement sensors

Measured physical quantity	Measurement units	Transformation equation
Rotation angle	deg	$\varphi_x = i\frac{360}{z}$, φ_x – rotation angle, i – current number of output pulses ($i \in 0\ldots z$), z – number of pulses per full revolution ($z \in 10^3\ldots10^6$)
	rad	$\varphi_x = i\frac{2\pi}{z}$
Rotation frequency	rpm	$f_x = \frac{n_x Z}{60}$, n_x – rotation speed, f_x – frequency of output rectangular pulses
Angular speed	rad/s	$f_x = \frac{\omega_x Z}{2\pi}$, ω_x – angular speed

The advantages of such sensors are: wide measuring range (from 10^3 to 10^6 rpm), simplicity of design, low load on the object of measurement due to the low moment of inertia of the moving part of the sensor, high noise immunity, almost unlimited service life. For dynamic measurements, their high resolution is extremely important, which is determined by the Z – the number of pulses per full revolution ($Z \in 10^3\ldots10^6$).

Based on the above, it becomes obvious the usage of digital tachometers by the vast majority of developers, which generalized block diagram for dynamic measurements of angular velocity, is shown in Fig. 1.

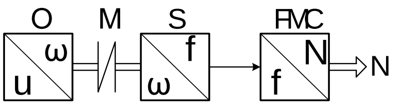

Fig. 1. Generalized block diagram of dynamic measurements ω_x: O – measuring object, u – supply voltage, ω – rotation frequency, angular speed, S – sensor, encoder, f – output pulse frequency, FMC – frequency measuring channel, N – the number of pulses at the output of the measuring channel

The third feature of dynamic measurements of angular velocity is the implementation of the measuring channel of the frequency of instantaneous values, which is based on the indirect method of frequency conversion f_x in parallel binary code N. In such measuring channels, the quantization of the period T_X, which is formed at the direct output of the counting trigger T, is carried out by the periods T_0 of the sample frequency f_0. As a result of such comparison of the measured T_X and sample T_0 of physical sizes receive numerical values of N angular velocity through the period – in even or not even periods. At dynamic measurements of angular velocity, it is necessary to have its numerical values in each period of frequency f_x at the output of the encoder, which in the literature is called frequency measurement in the "adjacent intervals". This is especially true for compatible measurements, the results of which are functional dependencies $\omega_x(t), \xi_x(t), M_D(t), M_D(\omega)$.

Such block diagrams are known and widely used by developers of information and measurement technologies [10]. Mathematical models that adequately describe the various transformation phases of information in angular velocity measurement channels remain unexplored here. The lack of such theoretical results is a scientific and applied problem, the solution of which will allow at the stage of development and design of hardware and software to model such basic metrological characteristics of the measuring channel as the transformation function, quantization and sampling errors, measurement range, aggregates will provide new knowledge in the field of metrological support of angular velocity dynamic measurements.

The aim of the work is to obtain mathematical models, which are a transformation function of the angular velocity measuring channel, the quantization equation and sampling errors, analytical dependences for estimating the measurement range in the form of lower and upper limits of measurement and speed [7].

1. Measuring channel of instantaneous angular velocity

The characteristic features of the structural diagram of the angular velocity measuring channel (Fig. 2) include the following:

1. Quantization of periods T_x by periods T_0 of exemplary frequency f_0 carried out in the logic circuit "AND" from the direct T or inverse $\overline{T}$ outputs of the counting trigger T, which is also called the period selection device [6].
2. The presence of a binary counter CT2, which counts the number of N sample periods T_0, which quantize the periods T_x or $\overline{T_x}$, formed, respectively, on the direct or inverse outputs of the counting trigger T;
3. The presence of a programmable interface for transmitting binary codes of the number of pulses N from the outputs of the binary counter CT2 in the ACC accumulator of the microprocessor system MPS, the main components of which are the CPU microprocessor, RAM and ROM constant memory.

The beginning of the measurement is the signal 1/0 – start/stop to the measurement object from the CPU microprocessor of the MPS microprocessor system through the parallel programmable PPI interface. The sensor shaft connected by a coupling to the shaft of the measuring object begins to rotate. The encoder (sensor) converts the angular velocity into a sequence of electrical signals, the frequency of which is determined [8, 9]

$$f_x = \frac{\omega Z}{2\pi} \quad (1)$$

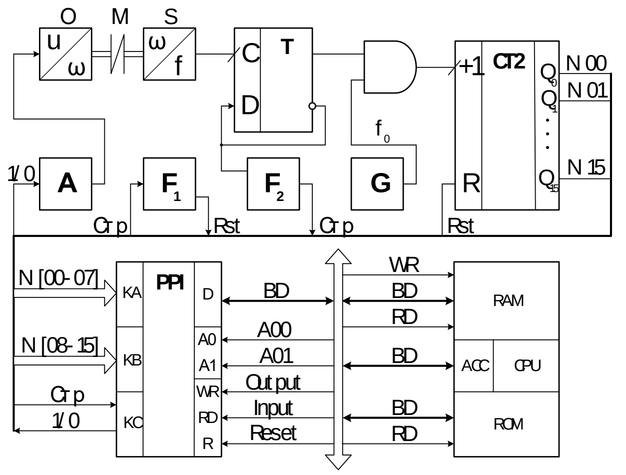

Fig. 2. Block diagram of the measuring channel of the angular velocity: T – trigger (period selection device); F_1, F_2 – shapers; A – measuring object adapter; G – sample generator f_0; CT2 – binary counter; PPI – parallel programmable interface; microprocessor system MPS, consisting of a CPU microprocessor and its dedicated ACC accumulator, RAM and non-volatile ROM. T_X – direct trigger output T; Res– zero setting of the binary counter triggers CT2; Cmp – signals for recording 2 bytes of information from the outputs N00, N01...N15 of binary counter CT2 in the buffer ports of the channels KA i KB interface PPI; BD – data bus; A00, A01 – lest significant bits of the address bus; Out – signal for writing information to the PPI; Input – a signal to read information from the PPI; Reset – zero signal of all interface ports PPI; WR – information recording signal в RAM; RD – information reading signal from RAM (ROM); 1/0 – start/stop of the measuring object

Rectangular output signals of the encoder with frequency f_x arrive at the C–input of the counting trigger T, at the direct output of which the period T_x of the encoders output frequency f_x is formed (Fig. 3).

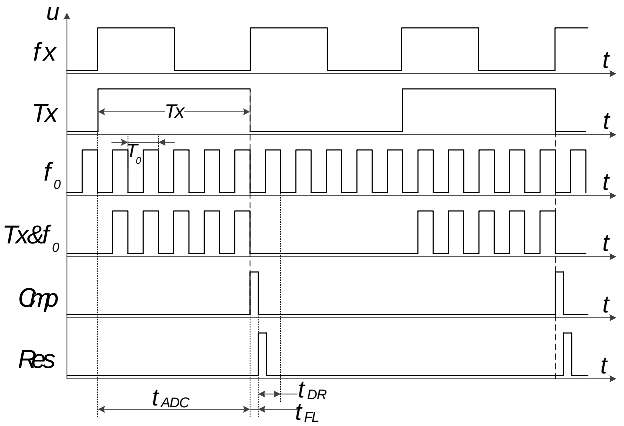

Fig. 3. Timing diagrams of the measuring channel

In the scheme of logical "AND" quantization takes place by comparing the measured physical quantity T_x with the sample T_0. As a result of such comparison the equations of transformation of the measuring channel of frequency of the instantaneous values giving the following function of transformation receive [2, 11]

$$N = \frac{T_x}{T_0} = T_x \cdot f_0 = \frac{f_x}{f_0} \quad (2)$$

To obtain the conversion function of the angular velocity measuring channel in instantaneous values, we substitute in the equation (2) the value of f_x from the equation (1), which uniquely connects the input value of the angular velocity ω with the output value of the rectangular pulse frequency

$$N = \frac{2\pi \cdot f_0}{\omega z} \quad (3)$$

The number of pulses N passing through the open "AND" gate is counted by the binary counter CT2. The obtained equation (3) shows that the static characteristic of such a measuring channel is nonlinear (Fig. 4).

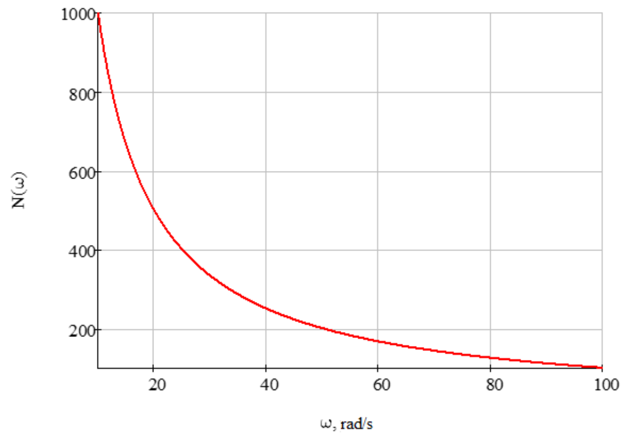

Fig. 4. Static characteristic: z = 628; $f_0 = 10^6$ Hz; $\omega \in 10 \cdots 100$ rad/s

The process of counting the periods T_0, coming to the input of the binary counter CT2, continues until the end of the period T_X. At the moment when the level of logic "1" quickly turns into the level of logic "0" (decline of the T_X) shaper F_1 at its output forms a short rectangular pulse Стр, according to which the number of pulses N given in binary code N00…N15 from the outputs of the binary counter CT2 are written to the buffer ports of the parallel interface PPI. At the same time the signal Стр sets to a single state the flag of readiness (Flag) which signals the accumulator ACC of the microprocessor CPU on completion of measurements and start of transmission of measurement information temporarily stored in the buffer ports KA and KB of the PPI. Upon completion of the signal Стр (on its trailing edge) the shaper F_2 at its output generates a short pulse Res, which on the R–inputs resets all the triggers of the binary counter CT2, and thus "prepares" it for the next cycle of measurements [1, 4, 5].

The process of transmitting the measurements information N00… N15 from the parallel interface to the microprocessor accumulator is controlled by an assembly program, the algorithm of which is as follows:

1. Begin.
2. Initialization of software of the measuring channel, as a result of which it is established:
   - The initial ADR address of the RAM buffer, in which the results of direct measurements of the T_X period will be recorded;
   - Organization of a software meter, which sets the number [i] of frequency measurements
3. Initialization of measuring channel's hardware:

3.1. Software setting of PPI operation mode channels:
   - channel KA[00-07] is programmed to mode "1" – synchronous input of the least byte of information from digital N [00-07] outputs of binary counter CT2 compatible with gating discharge channel KC04;
   - channel KB[08-15] is programmed to the mode "0" – a simple input of the high byte of information from the digital N [08-15] outputs of binary counter CT2;
   - KC [04] – the gate of the KA channel, which uses the signal Стр from the output of the shaper F1;
   - bit KC [00] to mode "0" – asynchronous output of the control signal of the measurement object;
   - KS [00] – software signal generation (1/0) for adapter A of the measurement object.

4. The next step is a software survey of the presence of a flag in the KC [04] bit. If KC [04] = "0", then the polling of the flag continues (conditional transition) until (looping) until the process of measuring the frequency in this period is completed KC [04] = "1". The subroutine of waiting for the flag presence will be called Flag, and the time of its execution will be marked t_{FL}.
5. After the appearance of the flag in the bit KC [04] = "1" first step is the reading of the low-order byte N [00… 07] from the buffer register (port) of the programmable PPI interface to the ACC accumulator of the MPS microprocessor system and then store it in RAM, and then leading byte N [08… 15].
6. Increases (increments) by one $ADR := ADR + 1$ RAM buffer address to store the next bytes of measured information.
7. Decreases (decrements) by one $i := i - 1$ the value of the measurement counter.
8. The contents of the measurement counter are checked to zero $i = 0$ If $i = 0$, then the measurement process ends. The conditional transition to the p.10 and to the operator "End" is carried out.
9. If $i \neq 0$, the driver program makes a conditional transition to the p.4 of this algorithm. The subroutine for the transfer of information from the parallel interface to the accumulator is called the Driver, and the time of its execution is denoted t_{DR}.
10. From equation (3) indirectly determine the array of numerical instantaneous values of the measured angular velocity
$$\omega = \frac{2\pi \cdot f_0}{Nz} \quad (4)$$
11. End.

This mode of information exchange between the external device (CT2) and the ACC accumulator of the microprocessor system is called – software mode.

2. Metrological characteristics of the measuring channel

As a result of replacing the analog value ω, which has an infinite number of values, with a continuous quantized value with a limited number of values in the form of a binary code N [00… 15], there is an absolute quantization error [11]

$$\Delta_{K} = \frac{1}{2}h = \frac{1}{2}T_0 \quad (5)$$

A more universal characteristic of accuracy is the relative quantization error

$$\delta_{K} = \frac{1}{N}100\% \quad (6)$$

Substituting the value of N in (6) from (3), we obtain the equation for estimating the relative quantization error

$$\delta_{K} = \frac{\omega \cdot z \cdot 100\%}{2\pi f_0} \quad (7)$$

Graphical representation of the relative quantization error dependence in the changing range of the measured value is shown in Fig. 5.

Analysis of the quantization error equation (7) and the results of its modeling, shown in Fig.5, show that the resolution z of the encoder and the value of the sample frequency f_0 are ways to reduce it.

Since the dependence of the relative quantization error on the change of the measured angular velocity is linear, it can be concluded that the normalized value δ_{KH} quantization error [7, 10] restricts the upper limit of measurement

$$\delta_{KH} = \frac{\omega_{max} \cdot z \cdot 100\%}{2\pi f_0} \quad (8)$$

From (8) we obtain the dependence for estimating the upper limit of the angular velocity measurement

$$\omega_{max} = \frac{2\pi f_0 \delta_{KH}}{z \cdot 100\%} \quad (9)$$

The dependence of the upper ω_{max} measurement limit on the normalized value of the relative error δ_{KH} is shown in Fig. 6.

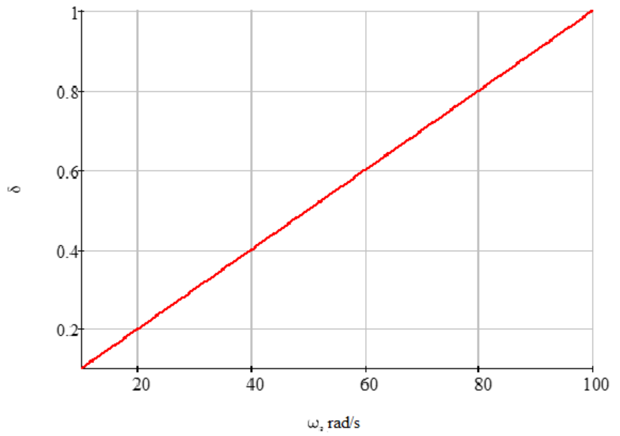

Fig. 5. Relative quantization error: z = 628; $f_0 = 10^6$ Hz; $\omega \in 10 \cdots 100$ rad/s

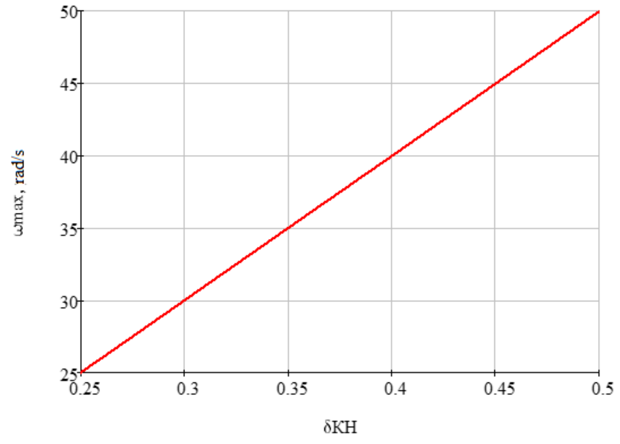

Fig. 6. Dependence of the upper ω_{max} measurement limit on the normalized value of the relative error δ_{KH}

The lower limit of angular velocity measurement is limited [7, 10] by the maximum capacity of the binary counter CT2

$$N_{max} = 2^n \quad (10)$$

where n is the bit rate of the binary counter CT2.

Taking into account (10), rewrite the transformation equation (3) and present it as follows:

$$N_{max} = 2^n = \frac{2\pi \cdot f_0}{\omega_{min} \cdot z} \quad (11)$$

From (11) we obtain the dependence for estimating the lower limit of the digital tachometer of instantaneous values

$$\omega_{min} = \frac{2\pi \cdot f_0}{2^n \cdot z} \quad (12)$$

The dependence of the lower limit of measurement ω_{min} on the bit rate n of the binary counter CT2 is shown in Fig. 7.

Therefore, in the range of change of angular velocity from the lower ω_{min} to the upper limit ω_{max} it is converted into binary code with a relative quantization error not exceeding the normalized value δ_{KH}.

As a result of such replacement of the analog value ω having an infinite number of values in the set range (from $\omega_{min}$to ω_{max}), a limited number of its instantaneous values in the specified time intervals T_D there is a sampling error [10]

$$\Delta_D = \frac{1}{2}T_D \cdot \frac{d\omega}{dt} \quad (13)$$

In (13) T_D the sampling step, which for the measuring channel (Fig. 2) according to the time diagrams (Fig. 4) is defined as:

$$T_D = t_{ADC} + t_{FL} + t_{DR} \quad (14)$$

t_{ADC} – the duration of the analog-to-digital conversion, which is equal to the measured period

$$t_{ADC} = T_X \quad (15)$$

t_{FL} – time spent executing the Flag waiting subroutine,
t_{DR} – time to run the Driver software subroutine.

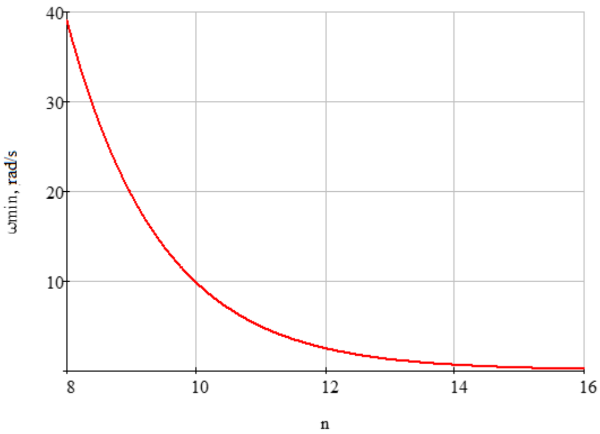

Fig. 7. Dependence of the lower limit of measurement ω_{min} on the bit rate n of the binary counter CT2

Determining the time [7, 10] of sampling the sum of time components for analog-to-digital conversion by hardware of the measuring channel circuit and time for execution of software drivers by software instruments of transmitting measuring information to the microprocessor system accumulator and its RAM is another feature of dynamic angular velocity measurement.

The maximum time required to execute the commands of the assembly subroutines Flag and Driver is estimated [11] by their initial listings.

$$t_{FL} = T_T \sum_{i=1}^{n} P_i \quad (16)$$

$$t_{DR} = T_T \sum_{j=1}^{m} P_j \quad (17)$$

where T_T – the period of the clock frequency f_T of the microprocessor CPU;
i – the number of commands in the Assembly subroutine Flag;
j – the number of commands in the Assembly subroutine Driver;
P_i, P_j – number of cycles in one command.

Taking into account (14) the sampling frequency of the angular velocity measuring channel is defined as:

$$f_D = \frac{1}{T_D} = \frac{1}{T_X + t_{FL} + t_{DR}} \quad (18)$$

We present the transformation equation of the encoder (1) as follows:

$$f_D = \frac{\omega_{max} \cdot z}{2\pi} \quad (19)$$

and we get the inequality

$$\omega_{max} \leq \frac{f_D \cdot 2\pi}{z} \quad (20)$$

which shows that the limiting factor of the upper limit of the angular velocity measurement is not only the normalized value of the quantization error δ_{KH} but also the value of the sampling rate f_D.

Rewrite (20) in a form convenient for further analysis of the upper limit of measurement [6, 11]

$$\omega_{max} \leq \frac{2\pi}{z \cdot (T_X + t_{FL} + t_{DR})} \quad (21)$$

Different modes are used for the I/O process: software, interrupt and capture (direct memory access).

The structural scheme (Fig. 2), time diagrams (Fig. 4) and the algorithm of the angular velocity measuring channel considered above belong to the program mode of operation, which is carried out under the control of the assembler subroutines Flag and Driver. The practical implementation of this mode of transmission is characterized by a minimum of hardware costs, which explains its low speed. This statement is well explained by the analysis (21) of the expression in parentheses in the denominator. Here are all the components that explain the maximum value of the sampling step

$$T_D = t_{ADC} + t_{Fl} + t_{DR} \Rightarrow max$$

and as a consequence, the lowest data transfer rate, which limits the upper limit of angular velocity measurement ω_{max}.

Unlike software, the interrupt mode is initiated by an external device (in our case, CT2). If you use the signal Стр as an "Interrupt Request", the microprocessor system MPS under the control of Driver software proceeds to transfer N [00..15] data from the digital outputs of the binary counter CT2 to the ACC accumulator of the CPU microprocessor. Therefore, the value of the sampling step is less at time t_{Fl} than in program mode and is determined accordingly

$$T_D = t_{ADC} + t_{DR}$$

Therefore, in the interrupt mode, the value of the upper limit of the angular velocity measurement

$$\omega_{max} \leq \frac{2\pi}{z \cdot (T_X + t_{DR})}$$

higher than in software mode.

In the "capture" mode, the transfer of information from the digital outputs of the binary counter CT2 to the CPU accumulator is carried out directly into the RAM memory of the microprocessor system MPS under the control of the controller direct access to memory.

3. Practical results

The algorithm of data transfer in the DMA mode is implemented using the scheme shown in Fig. 8. This measuring channel is implemented according to the frequency measurement scheme in the "adjacent intervals". And the last feature of dynamic measurements of angular velocity is the frequency measurement from the output of the encoder in the "adjacent intervals", and the measurement information transfer from the digital outputs to the accumulator in DMA mode.

The algorithm of the angular velocity measuring channel operation in the DMA mode is as follows:

1. Set the initial ADR address of the RAM memory by the software, which will store the binary code N [00-15] from the digital outputs in its cell CT2;
2. Software to install CT counter number of bytes to be transferred from digital outputs of CT2 counters to MPS RAM;
3. The external device (from the output of the logic gate "OR") sends to the DMA controller signal "DMA Request", which enters the CPU through the bus BC;
4. At this signal, the microprocessor responds with a signal to confirm direct memory access CDMA, puts its buses BA and BD in the third state and confirms its readiness to exchange information under the control of the controller direct access to DMA memory. This signal is the beginning of data transfer to the RAM.
5. The DMA controller sets the specified ADR address on the BA address bus;
6. An odd byte (T_X) from the digital outputs N [00-15] of the binary counter is fed to the BD data bus by the DMA controller. CT2.
7. The DMA controller generates an WR record of an odd byte of information in the RAM cell at the selected address.
8. The DMA controller automatically increments the initial ADR address by: (+1): = ADR + 1, thereby generating the address of the next cell to store the even ($\overline{T}_X$) byte of the measurement results array.
9. Decreases by (-1) the value of the LT byte counter: = LT-1. The current count of exchange bytes is performed.
10. When the value of the byte counter is zero LT: = 0, the DMA process ends, the DMA controller gives the CPU processor a signal End of DMA.
11. At the end of the DMA signal, the processor converts its BA address bus and the BD data bus to the active state and the PDP controller bus to the third state and proceeds to the execution of the interrupted DMA program.
12. If the value of the counter is not equal to zero, the controller proceeds to the transmission of the next byte of information (according to p.5 of this algorithm).

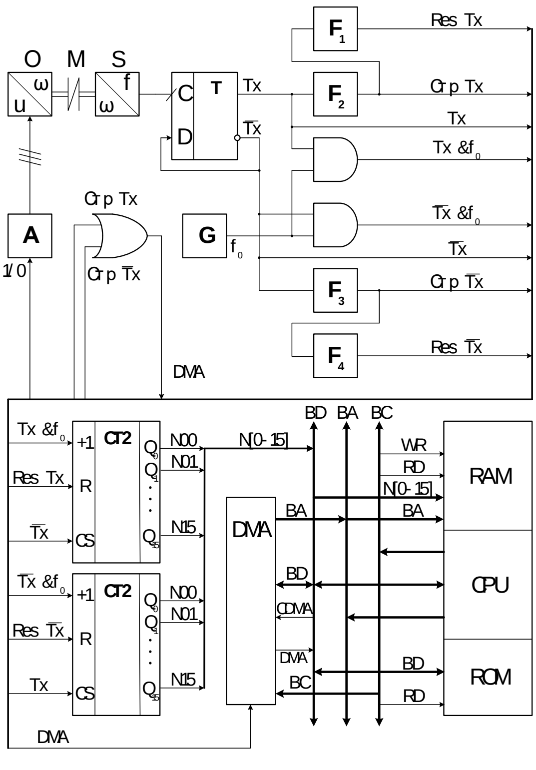

Fig. 8. Direct access to memory mode

In the DMA mode, the transmission of measurement information N [00… 15] from the digital outputs of the binary counter CT2 is carried out by hardware. Therefore, in this mode there are no time costs for execution of Flag and Driver subroutines (t_{FL} = 0, t_{DR} = 0). Therefore, in the DMA mode, the value of the upper limit of the angular velocity measurement is maximum

$$\omega_{max} \leq \frac{2\pi}{z \cdot T_X}$$

To increase the upper limit of measurement, it is necessary to propose adaptive algorithms for changing the resolution of the z encoder.

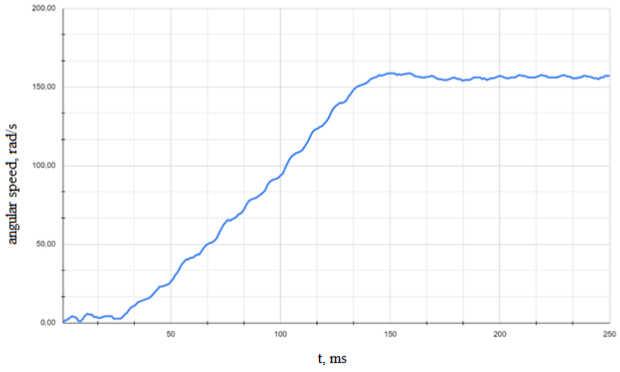

Fig. 9. The results of the experiment

Experimental studies were based on a prototype consisting of the object of measurement – three-phase asynchronous motor UAD-34 with a nominal speed of 1500 rpm, coupling shaft membrane type, encoder LIR-250A (z = 1500 marks per revolution) and debug board based on dual-core 32-bit microcontroller (MCU) TMS320F28379D, containing 1 MB of flash memory, 128 KB of RAM. This MK provides 12 32-bit general-purpose timers as well as 12 16-bit ADC channels, which is sufficient for this kind of dynamic measurements. The transient process for this object of measurement is shown in Fig. 9.

4. Conclusions

For the first time, the most significant features of angular velocity dynamic measurements, the numerical value of which is given in binary code, are highlighted in the paper. The main phases of measuring information transformation are established, which allowed to obtain new mathematical models in the form of transformation function, equations for estimating quantization errors, analytical dependences for determining the measuring range, which are the starting point for modelling physical processes in such digital measuring instruments.

Applying the methods of experimental computer science of reproduction, comparison and calculation on the example of indirect conversion of angular velocity into binary code for the first time analytically described the process of conversion of analog value ω_x into binary code N, the equation for estimating the absolute and relative quantization error is obtained and the measurement range is set, which provides the normalized value of the relative quantization error for angular velocity measuring channels with encoders.

The sampling error equation was obtained for the first time and it was proved that the limiting factor of the upper limit of angular velocity measurement is not only the normalized quantization error value δ_{KH}, as previously thought, but also the sampling frequency value f_D. Therefore, to expand the measurement range (by increasing the upper limit of measurement ω_{max}) it is proposed not only to increase the speed of analog-to-digital conversion hardware, but also to reduce the execution time of software drivers for transmitting measurement information to microprocessor memory. In this regard, the analytical dependences for estimating the upper limit of measurement for different modes of information transmission: software, interrupt, capture.

The practical implementation of the software mode of transmission of measurement information is characterized by a minimum of hardware costs and maximum execution time of the software driver, which explains its low speed, and therefore provides a minimum value of the upper limit of measurement ω_{max}. In the interrupt mode, the value of the upper limit of the angular velocity measurement is higher than in the program mode due to the reduction of the execution time of the software driver (t_{FL} = 0). The maximum value of the upper limit of the angular velocity measurement can be obtained using the transmission of measuring information in the DMA mode by providing the maximum speed in this mode ($t_{FL} = 0$, $t_{DR} = 0$).

In addition, the application of the results obtained in the work allows at the design stage (during physical and mathematical modeling) to assess the basic metrological characteristics of the measuring channel ω_x, which aims to reduce the development and commissioning of hardware and software and standardization of their metrological characteristics.

References

[1] Azarov A. D. et al.: Class of numerical systems for pipe-line bit sequential development of multiple optoelectronic data streams. Proc. SPIE 4425, 2001, 406–409.
[2] Azarov O. D. et al.: Static and dynamic characteristics of the self-calibrating multibit ADC analog components. Proc. SPIE 8698, 2012, 86980N.
[3] DSTU 2681-94. Metrology. Terms and definitions. Kyiv: State Standard of Ukraine, 1994.
[4] Kolobrodov V. G. et al.: Physical and mathematical model of the digital coherent optical spectrum analyzer. Optica Applicata 47(2), 2017, 273–282.
[5] Kolobrodov V. G. et al.: The diffraction limit of an optical spectrum analyzer. Proc. SPIE 9809, 2015, 98090F.
[6] Kukharchuk V. V. et al.: Discrete wavelet transformation in spectral analysis of vibration processes at hydropower units. Przegląd Elektrotechniczny 93(5), 2017, 65–68.
[7] Kukharchuk V. V. et al.: Information Conversion in Measuring Channels with Optoelectronic Sensors. Sensors 22(271), 2022 [http://doi.org/10.3390/s22010271].
[8] Kukharchuk V. V. et al.: Method of magneto-elastic control of mechanic rigidity in assemblies of hydropower units. Proc. SPIE 10445, 2017, 104456A.
[9] Kukharchuk V. V. et al.: Noncontact method of temperature measurement based on the phenomenon of the luminophor temperature decreasing. Proc. SPIE 10031, 2016, 100312F.
[10] Kukharchuk V. V. et al.: Torque measuring channels: dynamic and static metrological characteristics. Informatyka, Automatyka, Pomiary w Gospodarce i Ochronie Środowiska 3, 2020, 82–85.
[11] Kvyetnyy R. et al.: Modification of fractal coding algorithm by a combination of modern technologies and parallel computations. Proc. SPIE 9816, 2015, 98161R.
[12] Murzenko O., et al.: Application of a combined approach for predicting a peptide-protein binding affinity using regulatory regression methods with advance reduction of features. 10th IEEE International Conference on Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications IDAACS 2019, 1, 8924244, 431–435.
[13] Ornatsky P. P.: Automatic measurements and instruments. Higher School, Kiev 1980.
[14] Ornatsky P. P.: Theoretical foundations of information and measurement technology. Higher school, Kiev 1983.
[15] Osadchuk A. et al.: Pressure transducer of the on the basis of reactive properties of transistor structure with negative resistance. Proc. SPIE 9816, 2015, 98161C.
[16] Ostafiev V. A. et al.: Laser diffraction method of surface roughness measurement. Journal of Materials Processing Technology 63(1–3), 1997, 871–874.
[17] Podzharenko V. O., Kukharchuk V. V.: Measurement and Computer Measurement Technology: A Tutorial. UMKVO, Kiev 1991.
[18] Sena L. A.: Units of physical quantities and their dimensions. Nauka, Moscow 1977.
[19] Trishch R. et al.: Methodology for multi-criteria assessment of working conditions as an object of qualimetry. Engineering Management in Production and Services 13(2), 2021, 107– 141.
[20] Trishch R. et al.: Qualimetric method of assessing risks of low quality products. MM Science Journal 2021, 4769–4774.
[21] Tymchik G. S. et al.: Diagnosis abnormalities of limb movement in disorders of the nervous system. Proc. SPIE 104453, 2017, 104453S.
[22] Tymchik G. S. et al.: Distortion of geometric elements in the transition from the imaginary to the real coordinate system of technological equipment. Proc. SPIE 10808, 2018, 108085C.
[23] Vedmitskyi Y. G. et al.: New non-system physical quantities for vibration monitoring of transient processes at hydropower facilities, integral vibratory accelerations. Przegląd Elektrotechniczny 95(3), 2017, 69–72.
[24] Volodarsky E. T. et al.: Metrological support of measurements and control: A textbook. VSTU, Vinnytsia 2001.

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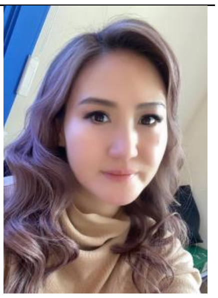

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