

RESOLVER-TO-DIGITAL CONVERTERS WITH THE ARCTANGENT FUNCTION TRANSFORMATION

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The work is devoted to the peculiarities of the construction of amplitude converters of type “angle-parameter-code”, in which arctangent function transformation is used when converting output signals of a resolver into a digital equivalent of movement. The features of the construction of brushless classical resolvers and varieties of their variable reluctance, in Russia known as reductosin, are considered. It allows to realize an electrical reduction, at which the sensor accuracy increases considerably. The principle of operation of the resolver, output signals of which contain reliable information about components of displacement of the rotor, is found out. Resolver-to-Digital Converter (RDC) corresponds to the postulate of the general theory of relativity on communication of space and time.

A special place among one-component “angle-parameter-code” converters is held by the structures using arctg-conversion, at which quadrant or octant range splitting of the transformation of angular displacement is used. In the first case, angular transformation is implemented by the digital signal processor (DSP) or microcontroller, and in the second one – by ROM with arctg insertion.

The structure and ratios necessary for calculation of movement by software and tabular implementation of arctangent function transformation. An original version of the analog-to-digital converter with arctg ROM is presented. Its capacity at identical length of the output code is four times less than the capacity of traditionally used ROM with a sine-cosine firmware. Octant representation of a full range transformation of the angle of rotation allows to generate an additional high order digit of the output code in comparison with a traditional quadrant band splitting. This not only improves the resolution of the conversion twice, but also simplifies coordination of samples at application of an electrical reduction with the reductosin.

Keywords: resolver-to-digital converters, classical and variable reluctance resolvers (reductosin), pulsewidth modulation, brushless motors, arctangent function transformation, ADC voltage ratios, read-only memory.

Introduction

The scope of work is actual as it is devoted to energy informatics (energoinformational interaction) [1] of the electric drive [2] and mechatronic systems (MS) [3]. The analysis of publications devoted to the development, research and implementation of a dateware of the process of the conversion of energy in the functional movement of the working mechanism, possessing property of a chronotope, provides the following tasks:

- features of the resolver functioning and its construction [4–10];
- formation of the Common Dateware on the basis of the conversion corresponding to the general theory of relativity in terms of the postulate of time and space communication [11–16];
- as sensors at Common Dateware are used inductive [17], optical [18] and magnetic-field [19] sensors. Most widely used are Synhros and Resolvers (R), possessing remarkable properties and high performance criteria [2, 7].

Resolver is a 2-phase micromachine

Resolvers are brushless type (Fig. 1) that is, the rotor excitation is ring transformer (RT) coupled to the shaft rotor winding. Many resolver applications operate with high speeds where the velocity error is significant source of measurement errors. Also, the signals of resolver are affected by the switching

noise due to pulse width modulation (PWM) of the motor inverter [3, 4]. Paper represents a solution for measuring the resolver signals for electric drive application without being affected by the speed and the switching noise due to PWM of motor inverter.

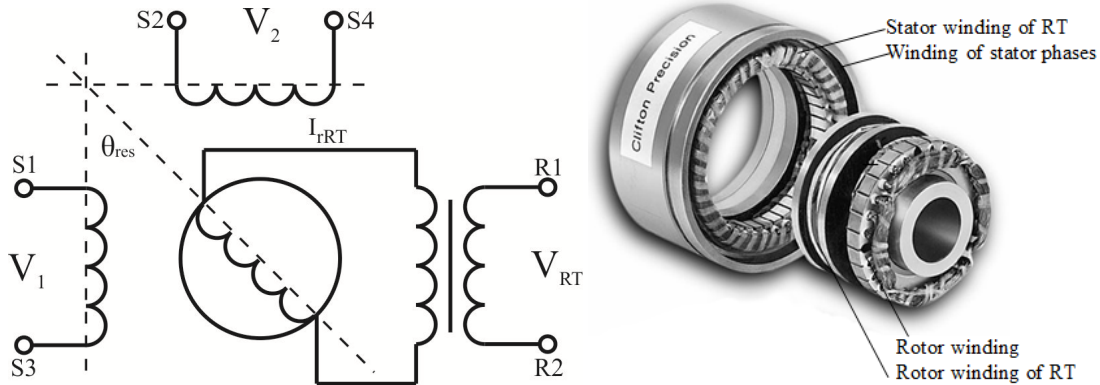


Fig. 1. The brushless classical resolver company Clifton Precision

The RT stator of brushless resolver (Fig. 1) is supplied from AC voltage $V_{RT} = V_{RTm} \sin(\Omega_e t + \varphi_e)$ of variable frequency Ω_e and phase shift of φ_e . The RT stator and rotor currents are I_{sRT} and $I_{rRT} = I_{rRTm} \sin(\Omega_e t)$, respectively. Resolver is a 2-phase AC machine. So, the electrical equations for stator windings of this machine are:

$$\begin{aligned} V_1 &= RI_1 + LSI_1 + s[(L_m \cos p_{res} \Theta_{me}) I_{rRT}] = \\ &= RI_1 + LSI_1 - L_m I_{rRT} p_{res} \Omega_{me} \sin p_{res} \Theta_{me} + L_m (\cos p_{res} \Theta_{me}) (s I_{rRT}); \end{aligned} \quad (1)$$

$$\begin{aligned} V_2 &= RI_2 + LSI_2 + s[(L_m \sin p_{res} \Theta_{me}) I_{rRT}] = \\ &= RI_2 + LSI_2 + L_m I_{rRT} p_{res} \Omega_{me} \cos p_{res} \Theta_{me} + L_m (\sin p_{res} \Theta_{me}) (s I_{rRT}), \end{aligned} \quad (2)$$

where Ω_{me} is the mechanical speed; Θ_{me} is the mechanical angle; p_{res} is the resolver number of poles; $V_1, V_2; I_1, I_2$ are the voltages and currents of stator 1 and 2 windings; R is the stator winding resistance; L is the stator winding inductance; L_m is the amplitude of mutual inductance of stator windings and rotor winding; $s = d/dt$.

In the no-load condition (high impedance of measuring circuits), for stator windings there will be no current and the current derivatives will be also zero ($I_1 = I_2 = sI_1 = sI_2 = 0$). So, the equations (1) and (2) will be:

$$V_1 = L_m (\cos p_{res} \Theta_{me}) (s I_{rRT}) - L_m I_{rRT} p_{res} \Omega_{me} (\sin p_{res} \Theta_{me}); \quad (3)$$

$$V_2 = L_m I_{rRT} p_{res} \Omega_{me} (\cos p_{res} \Theta_{me}) + L_m (\sin p_{res} \Theta_{me}) (s I_{rRT}). \quad (4)$$

The voltages (3) and (4) have two components: the first one (back-EMF) depends of excitation frequency Ω_e (because $I_{rRT} = I_{rRTm} \sin \Omega_e t$), speed (Ω_{me}) and position $\Theta_{res} = p_{res} \Theta_{me}$, the second one (EMF of transformation) depends of frequency Ω_e (because $s I_{rRT} = I_{rRTm} \Omega_e \cos \Omega_e t$) and position $\Theta_{res} = p_{res} \Theta_{me}$. This property of the signals V_1 and V_2 allows to eliminate errors due to the speed Ω_{me} . In the case of synchronous sampling of both signals V_1 and V_2 when $\sin \Omega_e t = 0$ and $\cos \Omega_e t = 1$, the current $I_{rRT} = 0$ and its derivative is maximal: $s I_{rRT} = I_{rRTm} \Omega_e \cos \Omega_e t = I_{rRTm} \Omega_e$. So, in (3) and (4), the back-EMF components will be absent and EMFs of transformation will be only position dependent with maximal amplitude $V_m = L_m I_{rRTm} \Omega_e$:

$$V_1 = L_m (\cos p_{res} \Theta_{me}) I_{rRTm} \Omega_e; \quad (5)$$

$$V_2 = L_m (\sin p_{res} \Theta_{me}) I_{rRTm} \Omega_e. \quad (6)$$

From (5) and (6), the angle $\Theta_{me} = \Theta_{res} / p_{res}$ may be calculated using standard software decisions.

Variable reluctance resolvers (VRR) have no windings on the rotor. Their primary and secondary windings are all on the stator, but the saliency (exposed poles) of the rotor couples the sinusoidal variation in the secondary with the angular position Fig. 2) [5, 6].

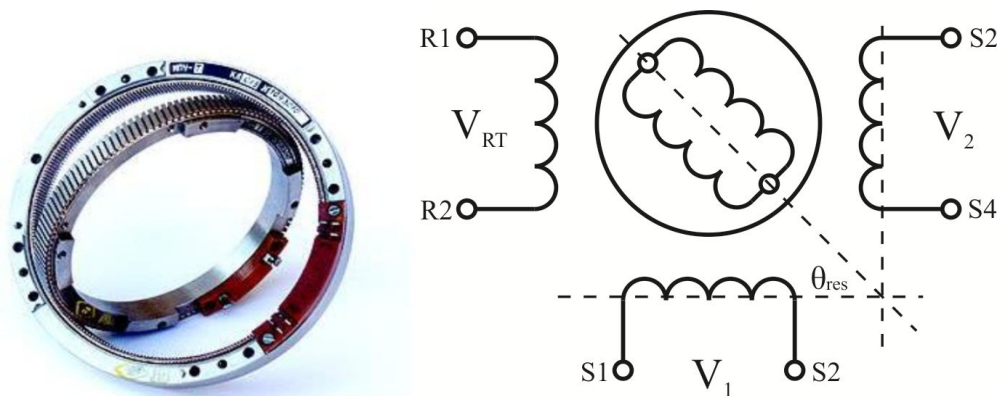


Fig. 2. Variable reluctance resolver (reductosin)

The structure of the RDC with digital signal processor

Converter realising the proposed method by *DSP* comprises (Fig. 3): exciting generator *EG*, *DAC* and analog voltage inverter *AVI* for *R* excitation; differential amplifiers *DA1* and *DA2* conditioning resolver output signals; *ADC* for converting of analog signals V_1 and V_2 into digital form D_1 and D_2 ; decoder software *DSW* for calculating of resolver angle $\Theta_{res} = \Theta_{me} p_{res}$ from D_1 and D_2 .

RDC (Fig. 3) is capable of outputting a good resolver signals two times per excitation period without being affected by the motor speed and by the switching noise due to a PWM signal of an inverter. In the tested system, the 14-bit AD converter for data conversion was used. That means $(4V/5V) \cdot 16392 = 13113$ bit resolution for peak-to-peak of the measured signal. There are $360 \times 60 \times 60''$ (arc seconds) in the 32 periods (2 times peak-to-peak) of the resolver with 32 poles signal. So, one bit (resolution) of the ADC corresponds to $1,544''$ (arc seconds).

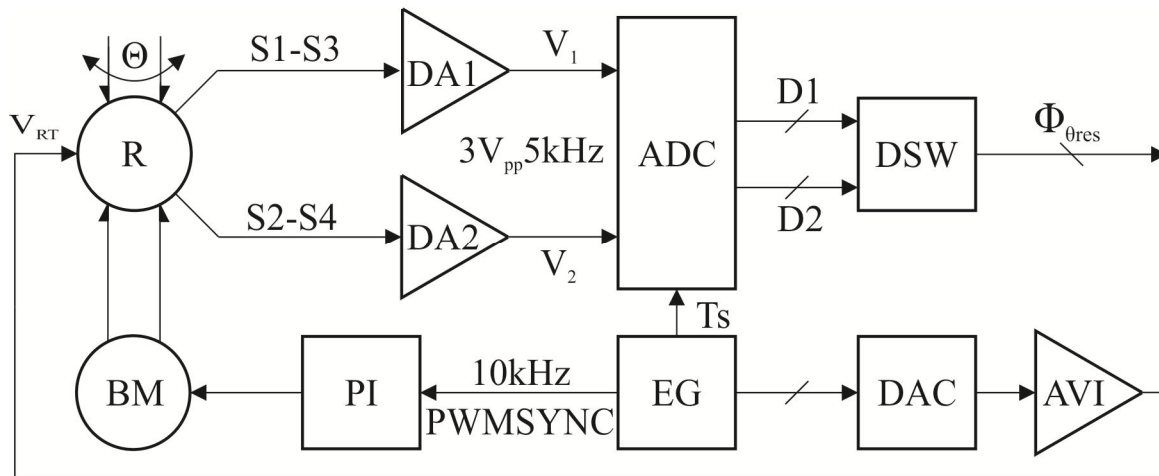


Fig. 3. Structure of the RDC with digital signal processor

An experiment has been set-up in order to validate the proposed solution. In this experiment, the modulation signal V_{RT} and PWM noise were completely disappeared from the digital signals D_1 and D_2 . For what concerns the accuracy of the position measurement, a comparison between the processed resolver data and the incremental encoder data has been performed. The tests were done with mechanical speeds of $0,01 \text{ rad} \cdot \text{s}^{-1}$ and $50 \text{ rad} \cdot \text{s}^{-1}$ respectively. Very small differences between the two measurements were achieved. An off line calculation allowed to evaluate that the overall measurement error of the proposed RDC was contained within the 12 bit ADC error (6 arc seconds of the rotating angle) and was speed independent.

The resolver and RDC working principle of is as follows Fig. 4.

The two output signals are modulated by the sine and cosine of the shaft angle. A graphical representation of the excitation signal and the sine and cosine output signals is shown in Fig. 4a. The sine signal has maximum amplitude at 90° and 270° and the cosine signal has maximum amplitude at 0° and 180° .

On the Fig. 4b the excitation current derivative sI_{rRT} , the PWM synchronism signal (PWMSYNC), sampling signal periods T_s , cosine signal of position $\cos p_{res} \theta_{me}$, output voltage V_1 and digital signal D_1 of 32-pole pair resolver after AD conversion by the motor speed of 937RPM and $T_s = 100 \mu s$.

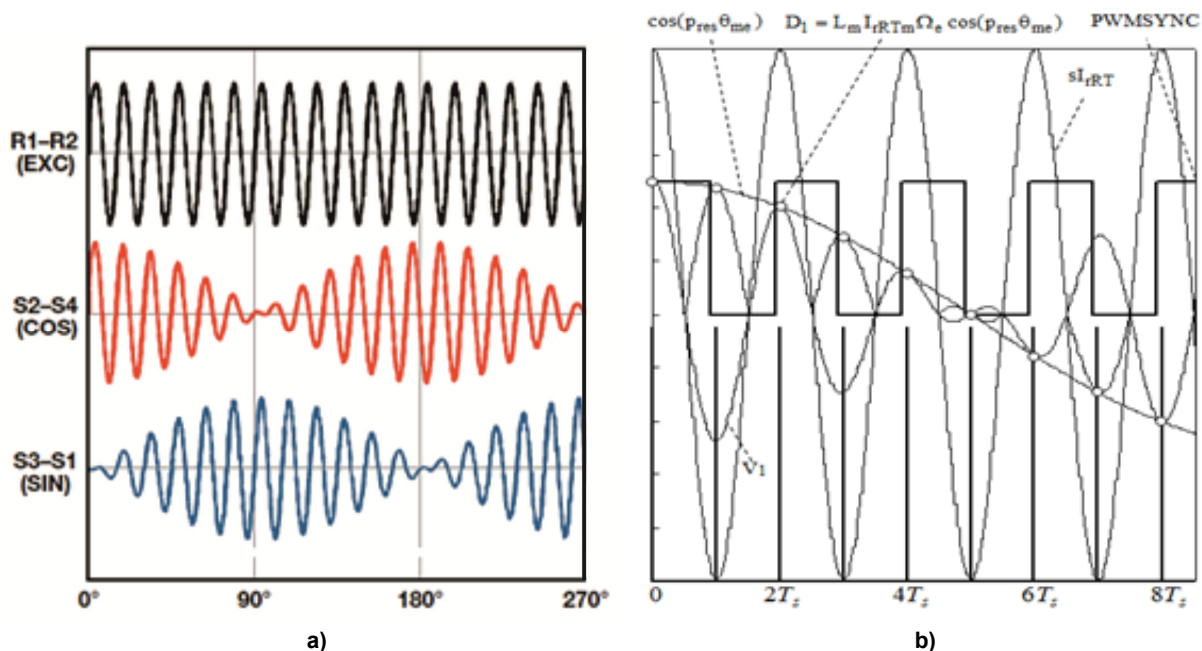


Fig. 4. Resolver and RDC working principle

The important feature RDC with digital signal processor

The first important feature of the used method is tuning of excitation voltage V_{RT} zero in the sampling period (T_s) of DSP for getting the maximal amplitude of resolver output signals V_1 and V_2 in the sampling moments T_s . This tuning is done by the phase shift of V_{RT} in the sampling period of the DSP during slow rotation of the motor. Tuning is finished by the maximum amplitude of signals V_1 and V_2 in the sampling moments T_s . Such procedure gives in the sampling moment the extremum of derivative of resolver rotor current sI_{rRT} , zero of resolver rotor current ($I_{rRT} = 0$) and zero back-EMFs in V_1 and V_2 – see (3) and (4).

The second important feature of the used method is synchronisation of *PWM* synchronism signal *PWMSYNC* with founded moment of resolver excitation. The *PWM* synchronism signal leading edge is tuned to get the minimal noise of measured signals. So, the system measures the resolver signals without being affected by the switching noise of inverter *PWM*. This phasing avoids the *PWM* interference on the resolver signals.

The third important feature of the used method is double sampling per excitation period. Position data D_1 and D_2 are read each sampling period at the time moments when the output signals amplitude is maximal. By the next sampling, the position data D_1 and D_2 are read as $-V_1$ and $-V_2$. So, digital signals D_1 and D_2 after conversion will have the amplitude modulated waveform of the exciting signal corresponding to the rotating angle $\Theta_{res} = \Theta_{me} p_{res}$ of the resolver as shown in Fig. 4b.

It is possible to calculate the angle, using a large number of known algorithms and various hardware [2, 3]. The simplest of these algorithms is a four-quadrant arctan signal conversion: $\Theta_{me} p_{res} = \text{arctg}_4(V_1/V_2)$.

Calculation of the function $\arctg(\beta)$ by algorithmic and tabular methods

The series expansion of the function $\arctg(\beta)$ is carried out on [17]:

$$\arctg(\beta) = \sum_{k=0}^{\infty} (-1)^k \cdot \beta^{2k+1} / (2k+1).$$

In the range of angles from 0 to 45 degrees for resolution of 20 bits 5 first members of a row are enough, taken with a 32-bit accuracy. Thus, after the measurement with the ADC, the calculation of the angle and its representation in the form of 0 to 1 for values from 0 to 2π takes 2 operations of normalization, one division, 5 multiplications, up to 8 additions and to 7 logical transitions on a short address. In total, no more than 40 cycles of a processor such as ARM Cortex-M3. For reduction of calculations Heron's formula is used. The calculations are integer (32 bits) with the normalization of up to 16 bits.

At calculation by the tabular method, the oktant with a required angle is determined by measured values of V_{sin} and V_{cos} and on the relation of values $|V_{sin}|$ and $|V_{cos}|$ the required angle is calculated by one of formulas [17]:

- to $V_{sin} > 0$ and $V_{cos} > 0$ and $|V_{sin}| < |V_{cos}|$, then $\varphi = \beta$,
- to $V_{sin} > 0$ and $V_{cos} > 0$ and $|V_{sin}| > |V_{cos}|$, then $\varphi = \pi/2 - \beta$,
- to $V_{sin} < 0$ and $V_{cos} > 0$ and $|V_{sin}| > |V_{cos}|$, then $\varphi = -\beta$,
- to $V_{sin} > 0$ and $V_{cos} > 0$ and $|V_{sin}| < |V_{cos}|$, then $\varphi = -\pi/2 + \beta$,
- to $V_{sin} > 0$ and $V_{cos} < 0$ and $|V_{sin}| > |V_{cos}|$, then $\varphi = \pi/2 + \beta$,
- to $V_{sin} > 0$ and $V_{cos} < 0$ and $|V_{sin}| < |V_{cos}|$, then $\varphi = \pi - \beta$,
- to $V_{sin} < 0$ and $V_{cos} < 0$ and $|V_{sin}| < |V_{cos}|$, then $\varphi = -\pi + \beta$,
- to $V_{sin} < 0$ and $V_{cos} < 0$ and $|V_{sin}| > |V_{cos}|$, then $\varphi = -\pi/2 + \beta$,

where β – an angle in the range of $0 \dots 45$ degrees ($0 \dots \pi/4$).

Further the value of $\text{tg}(\beta) = |V_{sin}|/|V_{cos}|$ is calculated and according to the table, depending on $\text{tg}(\beta_1)$, the value of β_1 is found, where $\text{tg}(\beta_1)$ – the nearest smaller tabular value of a tangent of angle, and a required angle

$$\beta = (\text{tg}(\beta) - \text{tg}(\beta_1))(C_0 + C_1 \cdot \beta_1 + C_2 \cdot \beta_1^2),$$

where C_0, C_1, C_2 – correction coefficients of correction of the algorithm error function. Such method provides resolution of 16 bits at the table size in 256 values.

Resolver-to-Digital Converter with arctangent ROM

Application of DSC (Fig. 3) or ARM to evaluate the function $\beta = \arctg \beta$ within an oktant in the algorithmic or tabular way leads to the reduction of the converting rate. Therefore, RDC with ROM should be preferred in high-speed MS. In MS, where “autophasing” [2] is not required, information on movement for self-switching of the electric motor can use the simplified algorithm of converting with arctg ROM. The offered [10] actantial representation of a full range of transformation, instead of a quadrant, at an equal speed allows to form additionally 3 highest weight discharge angles Θ . This is important in case of creation of a two-speed RDC, in which an additional bit is used for the matching of fine and coarse reading of MS. Speed of the conversion of output signals of resolvers to the digital equivalent of movement is also defined by speed of ADC of the relation of segments of tension in an oktant.

In the scheme shown in Fig. 5 in the first stage output signals of resolver R are converted to a code of a tangent of angle $\text{tg} \beta = V_s/V_c$, where β – the angle of rotation Θ , given in the first oktant. Simultaneously, the formation of three high-order digits of the angle Φ_Θ is carried out. RDC works as follows. Two signals, proportional to the current value of $\sin S$ and $\cos C$ of the angle Θ , arrive on inputs of the analog switchboard and the detector of oktants DO .

Their preliminary conversion is carried out either by individual demodulators DM of output signals of the resolver R or by peak detectors of the “memory access” type [10]. Three high-order digits of the code of the angle Θ are formed from the number of the oktant. By comparison of output signals of the resolver R with each other and with a zero-level number of the oktant is defined, which contains

the angle of rotation of a shaft of the resolver R . The octant in which $\sin \Theta > 0$, $\cos \Theta > 0$, and $\sin \Theta < \cos \Theta$ is accepted to be the first. Number of the octant increases counterclockwise. According to the known number of the octant signals, proportional to \sin and \cos of the angle Θ in the first octant, are determined:

$\sin \beta = |\sin \Theta|$, $\cos \beta = |\cos \Theta|$ in the 1, 4, 5 and 8th octants;

$\sin \beta = |\cos \Theta|$, $\cos \beta = |\sin \Theta|$ – in the 2, 3, 6 and 7th octants.

By linear analogue-to-digital conversion the code of the tangent of an angle β is defined, while as a reference signal in ADC is used a signal proportional to $\cos \beta$, and as a measuring signal – $\sin \beta$.

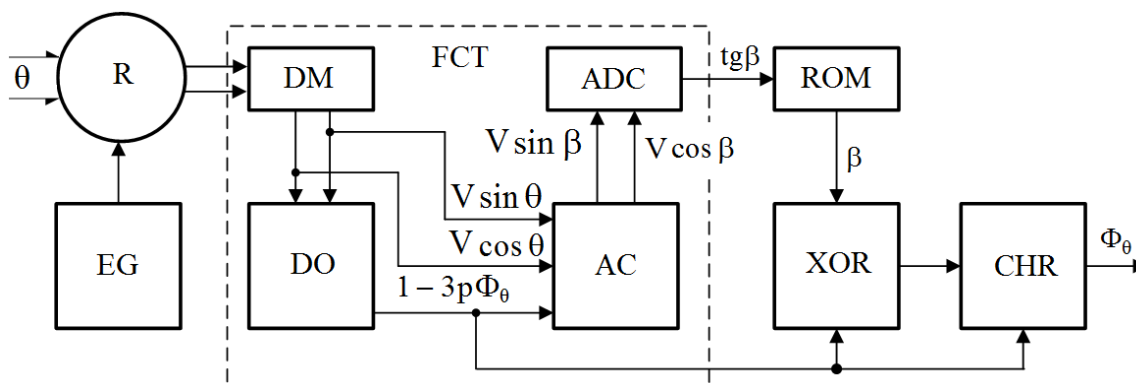


Fig. 5. Structure of the RDC with arctangent ROM

Construction of FCT on integrated circuits is considered in [12]. From the output ADC the code of $\text{tg} \beta$ arrives to address inputs of the read-only memory ROM , programmed under the law of the arctangent in the range of corners $0 - \pi/4$. ROM provides functional transformation of the input value $\text{arctg}(\text{tg} \beta) = \beta$, i.e. outputs the code of the angle β . A maximum code of the angle β corresponds to a zero input code $\text{tg} \beta$ $M_{max} = 2^j - 1$, where j – a digit capacity of ROM . The code of the tangent of a given angle β arrives at the address inputs of the ROM , which is used in a conversion device of the code $\text{tg} \beta$ to the parameter code β .

The code of the angle β is inputs to the EXCLUSIVE OR scheme (XOR), the other input of which is controlled by the least significant digit code of octants. Thus, in odd octants with the least significant digit code of octants equal to zero, XOR outputs the true code of the angle β , and in even octants with the least significant digit code of octants equal to one, it outputs the inverse code of the angle β , supplementing the angle β to $\pi/4$, i.e. equal to $(\pi/4 - \beta)$. From the output of XOR the code of the angle β or $(\pi/4 - \beta)$ goes to one of the inputs of the code holding registers CHR (see Fig. 5), to the other input of which comes the code of octants from DO . As a result of the summation of codes CHR outputs the code of the angle Φ_θ .

More than two-fold increase in conversion accuracy is achieved at simultaneous simplification of its circuit construction. Reducing of an instrumental error component by eliminating the additional code converter – the voltage gives an increase in the accuracy not less than in two times, and the exclusion of methodological error component allows further increasing of the conversion accuracy.

From the point of view of simplification the use of the one ADC and application of only standard integrated circuits is important, which reduces its cost. A significant advantage of such construction is its feasibility on standard electronic elements without the use of additional correcting ROM logic devices, which leads to the simplification of the device and improves the technological effectiveness of its production. An important factor is also the economy of ROM capacity, which at the same digit capacity of the output code is not less than 25% in comparison with sine-cosine RDC. At pulse powering of ROM the power consumption reduces, thereby implementing the device as a module based on the integrated or hybrid technology.

Conclusion

The progress in the sphere of RDC is caused by the improvement of technological processes and the development of new circuit solutions. The creation of integrated devices working at high speed and resolving power gives a number of advantages, including the reduction of the cost of products and the expansion of their functionality [7, 10].

Formation of digital equivalents of components of movement and its speed by the known RDC allows to give to the mechatronic system advantages of adaptation and self-organization [11], artificial intelligence, optimization of movement on time. To implement a modal [2], robust [6] and profile [2, 4] control it is necessary to increase the efficiency of MS energyinformatics.

Replacement of the elementary differential link which is traditionally used in all structures of automatic regulation to the more “intelligent” statistical link of a mathematical regression analysis of previous values is recommended. Ideologically differing from the well-known Kalman filter, link of this type allows to form in real time the current value of a control error by means of the mathematical regression analysis of all of its previous values, and thereby eliminate the influence of random fluctuations of signals in a feedback loop on the conversion accuracy. The synthesized digital tracking algorithm with a statistical link of regression processing allows to authentically receive up to 20 bits of the binary code of the angle measured by the angle-component solver [9]. The options of converting presented in the work indicate that modern microelectronics along with a sensor, having properties of a chronotope, fall within the postulate on spatio-temporal relation of the general theory of relativity, which was announced in 1916 by Albert Einstein [20].

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ПРЕОБРАЗОВАТЕЛИ «УГОЛ – ПАРАМЕТР – КОД» С АРКТАНГЕНСНЫМ ФУНКЦИОНАЛЬНЫМ ПРЕОБРАЗОВАНИЕМ

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Работа посвящена рассмотрению особенностей построения амплитудных преобразователей «угол – параметр – код», в которых при конвертации выходных сигналов резольвера в цифровой эквивалент перемещения применяется арктангенсное функциональное преобразование. Рассмотрены особенности построения классического бесконтактного резольвера и его разновидности – редуктосина, которые позволяют реализовать электрическую редукцию, существенно повышающую точность сенсора. Раскрыт принцип действия резольвера, выходные сигналы которого содержат достоверную информацию о составляющих перемещения ротора. Преобразователь «угол – параметр – код» соответствует постулату общей теории относительности о связи пространства и времени.

Особое место среди однокомпонентных преобразователей «угол – параметр – код» занимают структуры, использующие арктангенсное функциональное преобразование, при котором используется квадрантное или октантное разбиение диапазона преобразования углового перемещения. В первом случае тригонометрическое преобразование реализуется цифровым сигнальным процессором или микроконтроллером, а во втором – посредством ПЗУ с арктангенсной прошивкой. Приведена структура и соотношения, необходимые для вычисления перемещения путем программной и табличной реализации арктангенсной функции. Представлен оригинальный вариант аналого-цифрового преобразователя с арктангенсной ПЗУ. Его емкость при одинаковой разрядности выходного кода в четыре раза меньше емкости традиционно используемого ПЗУ с синусно-косинусной прошивкой. Октантное представление полного диапазона преобразования угла поворота, позволяет сформировать дополнительный старший разряд выходного кода по сравнению с традиционным квадрантным разбиением диапазона. Это позволяет не только повысить разрешение преобразования

в 2 раза, но и упростить согласование отсчетов при применении электрической редукции с редуктосином.

Ключевые слова: преобразователь «угол – параметр – код», классический и верньерный резольвер резольверы, широтно-импульсная модуляция, арктангенсное функциональное преобразование, АЦП отношения напряжений, постоянное запоминающее устройство.

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