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PHASE MEASUREMENT SYSTEM BASED ON EMBEDDED MICROCOMPUTER

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Abstract. *Theoretical considerations concerning data domain transformation implemented into a digital phase meter, as an embedded computer system, are presented in this paper. Details related to a functional hardware structure are given. The algorithms for autocalibration, coarse and fine phase shift measurements are described. Experimental results indicate that for 14 bits resolution and operating frequency range from 1 kHz up to 500 kHz the achieved meter's accuracy is less than 0,025 degree.*

1. INTRODUCTION

The advent of microprocessor has provided the means of involving intelligence into many everyday facilities such as washing machines, motor vehicles, medical equipment, telecommunication, etc. The main emphasis is on use the of microprocessors embedded in the systems to provide greater power, flexibility, effectiveness, reliability [1]. Having a microprocessor in the device means that removing bugs, making modifications, or adding new features are only matters of rewriting the software that controls the device.

Contemporary electronic measurement systems, as typical representatives of embedded computer systems, have become complicated machines which can perform complex tasks in a large variety of environments. Multipurpose, multifunctional measurement systems are now capable of performing tasks that were impossible ten years ago [2]. The focus of our interest in this paper is realization of a digital phase meter as a basic building block of one complex multifunctional embedded electronic measurement system.

Principles of measuring phase difference between two signals of identical frequency are given in [3], [4], [5] and [6]. In general, all methods can be classified as analogue, digital or those based on sampling [7] and [8]. More details concerning classification, accuracy and operating range of digital phase metters can be found in [9]. Bearing in mind that the hardware structure of our digital phase metter must be simple, highly accurate and part of an embedded system, we decide here to adopt the principle of a

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digital phase metter, and describe its internal structure. Additionaly, we give the implemented algorithm and we discuss experimental results.

The paper is organized as follows: Definition of embedded system is given in Section 2. Basic concepts related to data domain transformations are given in Section 3. Section 4 deals with a global structure of the proposed phase meter. Its basic building blocks: Signal switcher, Phase detector, Integrator, A/D converter and Microcomputer are briefly described. In Section 5, details concerning the implementation of the algorithm are given. Experimental results are presented in Section 6. Conclusion is given in Section 7.

2. DEFINITION OF EMBEDDED SYSTEM

Embedded systems (ESs) are computers incorporated in consumer products or other devices in order to perform application specific functions. ESs are found in a variety of common electronic devices, such as consumer electronics (cell phones, digital cameras, camcoders, videocassete recorders, portable video games, personal digital assistants), home appliances (microwave ovens, thermostates, home security systems, washing machines, and lighting systems), office automation (fax machines, copiers, printers, and scanners), business equipment (cach registers, alarm systems, card readers, product scanners), and automobiles (transmission control, cruise control, fuel injection, antilock brakes, active suspension). ESs have several common characteristics that distinguish such systems from other computing systems:

1. Self-functioned – An ES usually executes a specific program repeatedly.
2. Tightly constrained – ES often must cost just a few euros, must be sized to fit on a single chip, must perform fast enough to process data in real-time, and must consume minimum power to extend battery life or to prevent the necessity of a cooling fan.
3. Reactive and real time – ESs must continually react to changes in the system's environment and must compute certain results in real-time without delay.

3. DATA DOMAIN

A data-domain concept was for the first time developed by Malmstadt and Enke [10]. According to their idea the measuring process can be considered as a sequence of intra and inter domains mapping, i.e. conversions. Namely, using this concept it is possible, in one visual manner, to represent the data mapping process. In general, the main aim of the measuring process is directed towards: (i) correct choice of the inter/intra-mapping path through data-domains; and (ii) reducing to minimum the measuring errors. The data-domain concept will be used as a guide during process of the proposed digital phase metter design.

4. PHASE-METER: A GLOBAL STRUCTURE

A global functional structure of the phase-meter is given in Fig. 1. Both, s_0 and s_x are squarewave periodical signals (Fig. 2). We assume that: (a) s_0 is a reference signal, (b) φ_x

corresponds to an unknown phase difference between signals s_0 and s_x; (c) $-\pi \le \varphi_x \le \pi$, and φ_x is presented on the display as a N-digit signaed number b_x. Phase shift measurement is described by the transformation f_m, which can be represented as

$$f_m : \varphi_x \to b_x$$

The transformation f_m is defined as

$$f_m = f_{DSP} \otimes f_{MC} \otimes f_{ADC} \otimes f_{INT} \otimes f_{PHD} \tag{1}$$

where: f_{PHD} – phase-shift into time-interval mapping,
f_{INT} –voltage to digital interdomain mapping,
f_{MC} –mapping within the digital domain,
f_{DSP} –digital to observation domain mapping.

Further, we assume that the transformation f_{DSP} is ideal, i.e. there are enough digits for result displaying.

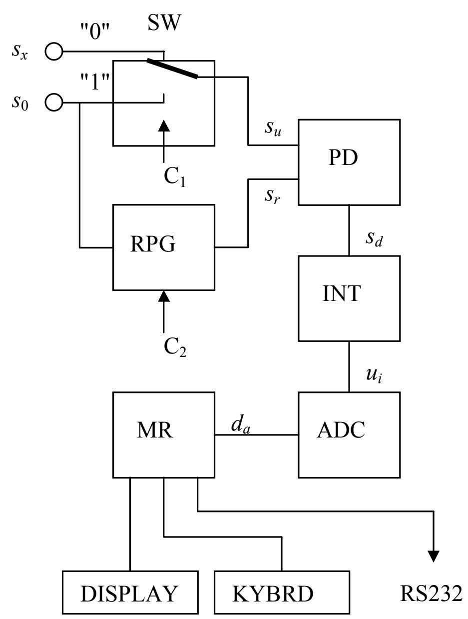

Fig. 1. Functional structure of the phase meter

4.1 Signal switcher

The switcher, SW, selects one of the input signals, s_x or s_0 . The select function is defined by a control signal C_1. The switcher provides automatic input signal selection and does not involve additional phase-shift. A possibility to select input signal with known (fixed) or unknown phase shift allows automatic switching between the following two operating modes: (i) calibration, and (ii) unknown phase-shift measurement.

4.2 Referent phase-shift generator

The referent phase-shift generator, RPG, generates the referent signal s_r. The phase-shift φ_r between signals s_0 and s_r defines state of control signals C_{2i}, i=0,1,2,3, and it is programmed in 2M steps according to the following relation

$$\varphi_r = d_{c2}\frac{\pi}{M} \tag{2}$$

where: d_{d2} – corresponds to a state of the control signal C_{2i},

$\frac{\pi}{M}$ – referent signal phase-shift quantum.

The RPG performs interdomain mapping from digital into time-interval domain. The mapping process is defined as

$$f_{RPG} : d_{c2} \rightarrow \varphi_r$$

As a hardware resource, the RPG is used to obtain several subranges (2M), i.e. to increase resolution during the measuring process.

4.3 Phase detector

The phase detector, PD, performs intradomain transformation of the measured value within the time-interval domain. Concretely it provides conversion of a phase-shift into time-interval subdomain.

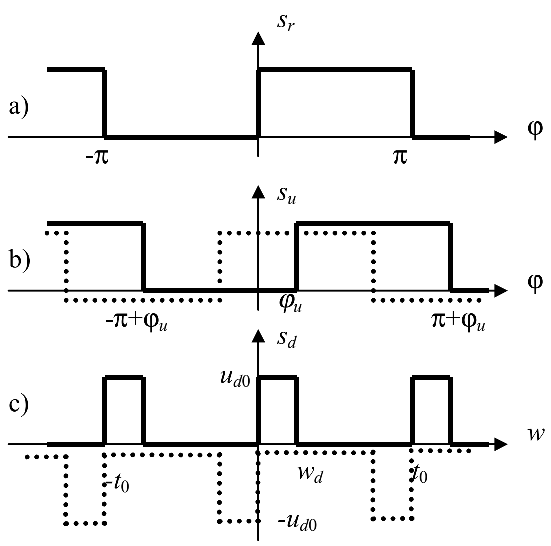

Fig. 2. Input and output signals of the PD

$$f_{PD} : \varphi_u \rightarrow t_d$$

Signals s_u and s_r drive PD's inputs. The signal s_d is generated at its output. In Fig. 2 are presented with solid (dashed) lines waveforms of input and output signals for $\varphi_u > 0$ ($\varphi_u < 0$). The signal s_d is defined as

$$s_d = U_{d0} sign(\varphi_u)(s_r \oplus s_u) \tag{3}$$

where: U_{d0} – amplitude of a detected signal,
$\oplus$ – point to Exclusive OR operation,
s_r, s_u – quantities that take values 0 or 1.

As it can be seen form Fig.2, the period of the signal s_d, denoted as t_0, is twofold shorter with respect to a period of signals s_u and s_r. The corresponding transformation function, according to Fig.2, can be written in a form

$$f_{PD} : t_d = \frac{t_0}{\pi} \varphi_u \tag{4}$$

The integrator, INT, performs interdomain transformation from time-interval into voltage subdomain.

$$f_{INT} : t_d \to u_i$$

where: f_{INT} – integrator's transformation,
u_i – analog voltage at the output of the integrator.

If we assume that the signal input amplitude of the integrator does not change during the integration period, the output voltage, according to Fig. 2c, is defined as

$$f_{INT} : u_i = \frac{1}{\tau} \frac{u_{d0}}{t_0} T_{\text{int}} t_d \tag{5}$$

4.4 Analog to Digital Converter

The analog to digital converter, ADC, performs interdomain transformation of the analog input u_i into data d_a . The mapping function is defined as

$$f_{ADC} : u_i \to d_a$$

If during the measuring process an error is less than $|\varepsilon_{ADC}| = \frac{1}{2} LSB$, then we have

$$f_{ADC} : u_i = \frac{u_{FS0}}{2^{K-1}} d_a \tag{6}$$

where: u_{FS0} – full scale range of the ADC and is defined by its reference voltage,
2^K – resolution of the ADC.

4.4 Microcomputer

The microcomputer generates all control signals in Fig.1. Additionally, the built-in software provides intradomain mapping within the digital domain, and includes activities such as estimating of the phase-shift in a digital domain, data processing, data formatting for displaying, etc. The f_{mc} can be determined having in mind the main goal of the measuring process - the realisation of transformation f_m without losses. Bearing in mind that f_{DSP} is an ideal subtransformation, then subtransformation f_m to be ideal, the following has to be valid

$$f_m = (f_{ADC} \otimes f_{INT} \otimes f_{PHD})^{-1}$$

As a result of the above mentioned composition of subtransformation we obtain

$$d_u = \frac{d_{FS}}{2^{K-1}} \frac{u_{FS0}}{u_{d0}} \frac{\tau}{T_{\text{int}}} d_a \tag{7}$$

where: d_u – corresponds to numerical presentation of φ_u,
d_{FS} – numerical value of a full scale input phase,
K – number of quantization steps of the ADC.

4.5 Basic relation

We shall define now some basic quantities crucial for determining the unknown phase-shift. Let us consider a situation when the SW (Fig. 1) is in position "1", and the control signal C_1=0. Then we have $\varphi_u = \varphi_x - \varphi_r$. In order to increase the resolution during measuremment we propose a method based on dividing the measuring range into several subranges. Additionally, we introduce the following definitions:

Def_1 Middle of measuring range, φ_c corresponds to a quantity of phase-shift, which in a digital domain for $C_1 = 0$, is mapped into a value $d_a = 0$.

Def_2 Measuring range, φ_w, represents maximal phase shift with respect to φ_c, for $C_1 = 0$,

Def_3 Single integration period, T_{INT0}, corresponds to integration period, when the condition $\varphi_u = \pi$ is fulfilled, during which a value of $d_a = 2^{K-1}$ is obtained.

According to these definition the following relations can be written

$$d_a = 2^{K-1} \frac{T_{\text{int}}}{T_{\text{int}0}} \frac{1}{\pi} \varphi_u \tag{8}$$

$$d_u = \frac{d_{FS}}{2^{K-1}} \frac{T_{\text{int}0}}{T_{unt}} d_a \tag{9}$$

$$\varphi_w = \frac{T_{\text{int}0}}{T_{\text{int}}} \pi \tag{10}$$

A detailed mathematical procedure concerning calculation of above equations is given in [9]. Analyzing [8-10] we can conclude the following:

- The quantity d_a corresponds to equivalent of unknown phase-shift in a digital domain, and depends on T_{INT}/T_{INT0}. By adjusting this ratio, the quantity d_a can take a value which is suitable for displaying in corresponding units.

- Physical parameters of the phase-meter are mapped into same relation, T_{INT}/T_{INT0}. If this ratio represents an integer number, all computation in a digital domain can be derived as deterministic, i.e. the remainder as a consequence of arithmetic division does not appear.
- The quantity φ_w depends on both the integration period T_{INT} and T_{INT0}. In this manner, during coarse and fine phase-shift measurement, it is possible to adjust the width of the measuring subrange.

5. IMPLEMENTATION OF THE ALGORITHM

In Section 1 the basic idea of the algorithm is defined. It is based on dividing the measuring process into two steps: coarse and fine phase-shift measurement. Having in mind that the system is realized as an embedded computer system, the built-in software provides operating conditions for performing all intra-, and inter-domain mapping transformations with minimal losses. By definition, constituents of the software are procedures for compensation of offset errors, adjustment of proportionality coefficient, coarse and fine phase-shift measurement, and others.

The measuring process can be decomposed into several phases. We start from (7), from which we see that in order to determine the unknown phase-shift in a digital domain, it is necessary for all subtransformations to know the quantities of all constants of proportionality. At the beginning, for known and fixed phase-shift the integration period for an ideal transformation is determined. After that, a correct wide for measuring range is selected and coarse and fine phase-shift measurement is performed. At the end the unknown phase-shift in digital domain is determined and the result displaying follows.

The measuring process consists of the following three tasks:

- Calibration - constant of proportionality for function fm is adjusted
- Measurement - coarse and fine phase-shift measurements of unknown phase-shift are performed
- Data processing - the result is determined and its displaying follows.

Let us point to specific activities of each task. In order to make the explanation more clear, the quantities d_a and T_{INT} during each task will be denoted as d_{aj} and T_{intj}. The index j = 1 points to the quantity during calibration, j = 2 corresponds to coarse, and j = 3 to the fine phase-shift measurement.

5.1 Calibration

The calibration procedure represents a sequence during which the coefficient of proportionality of the transformation f_m is adjusted. Analyzing the conditions under which the ideal transformation is carried out, we conclude that the constant of proportionality can be adjusted in one of the following two ways:

- by calculating the parameter quantities of the phase meter,
- by trimming a corresponding parameter of the transformation f_m.

Namely, in a concrete case the period of integration T_{int} is adjusted. During the calibration procedure the value T_{int} is determined, so that the composition of subtransformations f_{ADC} defines the following mapping

$$f_{ADC} : \varphi_{cal} \to d_{cal} \tag{11}$$

In a concrete case the known phase shift $\varphi_u = \varphi_{cal}$ is mapped into a known numerical value at the ADC's output, denoted as d_{cal}. For d_{cal} we have

$$d_{cal} < 2^{k-1} \tag{12}$$

The calibration is performed under the following conditions $C_1 = 1$, $d_{c2} = -1$, $T_{int} = T_{int1}$

The calibration procedure is iterative one. During each measuring cycle T_{int1} is defined, and the value d_{a1} is accepted. After that, according to difference (d_{cal} - d_1), T_{int1} is corrected. The measuring process is repeated until the following condition is fulfilled

$$d_{cal} - d_{a1} = 0 \tag{13}$$

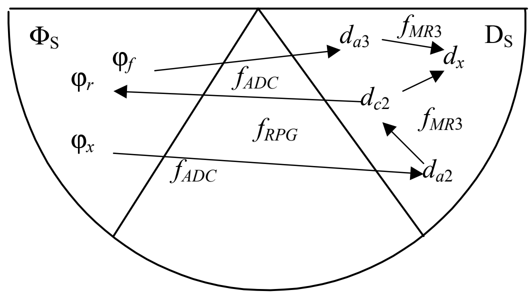

Fig. 3. Data transformation mapping

If for the last calibration step we use notation $d_{a1} = d_{cal}$ and $T_{\text{int }1} = T_{cal}$, then we can write

$$T_{\text{int}0} = \frac{2^{k-1}}{Md_{cal}} T_{cal} \tag{14}$$

According to (14) we can conclude that with correct choice of d_{cal}, value $T_{\text{int}0}$ can be determined with minimal rounding error during arithmetic processing. More details which relate to the choice of d_{cal} are given in the next subsection.

5.2 Measurement

The measurement phase consists of the following two steps: coarse and fine phase shift measurements. During both steps the phase shift is mapped into a digital domain. The mapping path is sketched in Fig. 3.

As can be seen from Fig. 3, at the beginning, the unknown phase shift is mapped into value d_{a2}. Implementing intradomain mapping, defined by f_{MR}, the coarse phase shift, d_{C2}, is determined. Subsequent sequence relates to mapping the value d_{C2} from a digital domain into a phase shift subdomain. The subtransformation which defines this mapping, denoted as f_{GRF} in Fig. 3, is performed by RPG. The RPG drives the input of PD (Fig. 1). The fine phase shift is mapped in a digital domain into value d_{a3}.

5.3 Coarse phase shift measurement

During this step, the coarse value of the unknown phase shift is assessed, i.e. the measuring subrange, R(m), is determined. Initial conditions are $C_1 = 0$, $d_{C2} = 0$, $T_{int} = T_{int2}$

From (7-10) that with goal to determine d_{a2} it is necessary to define the value of integration period T_{int2}. This period is determined under the condition that phase meter measuring range encircles the area in which φ_x is defined. If we assume that $\varphi_w=\pi$, then for the integration period we obtain

$$T_{int\,2} = \frac{1}{M}\frac{2^{k-1}}{d_{cal}}T_{cal} \tag{15}$$

In the case for d_{a2} we obtain

$$d_{a2} = 2^{k-1}\frac{1}{\pi}\varphi_x \tag{16}$$

Assessment of the measuring subrange R(m) represents a goal of the coarse phase shift measurement, and is equivalent to the estimation of value m. Procedure for assessment of m is based on relation which defines ownership of subrange R(i). Value m is obtained using the following formula

$$m = \frac{M}{d_{FS}}d_{a2} \tag{17}$$

5.4 Fine phase shift measurement

During this step a fine phase shift quantity in a digital domain, denoted as d_f, is determined. The mapping composition in a digital domain has a form

$$f_m : (\varphi_x - \varphi_r) \to d_f \tag{18}$$

Initial conditions are: $C_1 = 0$, $d_{C2} = m$, $T_{int} = T_{int3}$ where value m is determined during the previous step. The resolution with which the fine phase shift is determined is crucial for result presentation. According to (9), we can conclude that the resolution with which the fine phase shift is determined depends on integration period T_{int3}. Accordingly, in the sequel, the fine phase shift is determined for two characteristic cases that relates to choice of T_{int3}, CASE_A and CASE_B.

CASEA - The integration period is determined according to the following relation

$$T_{int3} = 2MT_{int\,0} \tag{19}$$

Then having in mind (14) we obtain

$$T_{int\,3} = \frac{2^k}{d_{cal}}T_{cal} \tag{20}$$

The fine phase shift in a digital domain, d_f, can be represented as

$$d_f = \frac{d_{FS}}{2M}\frac{1}{2^{k-1}}d_{a3} \tag{21}$$

CASEB - We determine the integration period, so that the relation

$$\frac{T_{cal}}{T_{\text{int}3}} = \frac{1}{2} \tag{22}$$

is valid. Namely,

$$\frac{T_{\text{int}0}}{T_{\text{int}3}} = \frac{2^{k-1}}{2Md_{cal}} \tag{23}$$

Finaly, the value d_f can be written as

$$d_f = \frac{d_{FS}}{2Md_{cal}} d_{a3} \tag{24}$$

Analysing results according to which values $T_{\text{int}3}$ and d_f are determined, we conclude that CASEA is partial solution for CASEB and is valid for $d_{cal} = 2^{k-1}$.

5.5 Result processing

During this phase, according to the results which relate to fine and coarse phase shifts the total amount of the phase shift is determined, and after that the result is displayed on the numerical display. Assessment of unknown phase shift in a digital domain represents an intradomain transformation within the digital domain. The unknown phase shift in digital domain, d_x, can be represented in the following form

$$d_x = \frac{d_{FS}}{M} m + \frac{d_{FS}}{2Md_{cal}} d_{a3} \tag{25}$$

By rearranging (25) we obtain

$$d_x = \frac{d_{FS}}{2Md_{cal}} (m2d_{cal} + d_{a3}) \tag{26}$$

Analyzing (25) we can recognize that measurement resolution is defined as

$$d_r = 2Md_{cal} \tag{27}$$

and the quantity

$$d_\Delta = \frac{d_{FS}}{2Md_{cal}} \tag{28}$$

point to the quantum of measured phase shift. Both of them can be adjusted by the choice of d_{cal}.

Let consider now the size of the phase shift quantum into the phase shift subdomain. The phase shift quantum is given as

$$\varphi_\Delta = \frac{\varphi_{FS}}{2M\,2^{k-1}} \text{, for-CASEA} \tag{30}$$

$$\varphi_\Delta = \frac{\varphi_{FS}}{2Md_{cal}} \text{, for-CASEB} \tag{31}$$

Determine now, for both cases, the exact value of the phase shift quantum φ_Δ. The quantum can be given in radians or degrees. This can be achieved if we use 3.14 or 180 for φ_{FS}, respectively. Also, we will define the values $M = 8$ and $K = 10$, which correspond to the phase meter structure given in Fig. 1 with 16 measuring subranges and built in 10-bits ADC, respectively.

For CASEA, the measurement is performed with greatest resolution, the value of phase shift quantum is rational number and is approximately equal to 0.000383 rad or 0.0219726 ^{o}. In order to determine the phase shift quantum for CASEB depending on the units in which the phase shift is represented on the display, we will select characteristic values for d_{cal}. If d_{cal} = 393 and the result is displayed in radians ($\varphi_{FS} = \pi$), the value of the phase shift quantum is φ_{Δ} =0.0005rad, while for d_{cal} = 450 and if the result is displayed in degrees (φ_{FS} = 180), the value of the phase shift quantum is $\varphi_{\Delta} = 0.025^{o}$.

6. EXPERIMENTAL RESULTS

After ralization of the described digital phase meter, numerious measurements were performed. Here we present the crucial ones.

The transfer function of a phase meter is pictured in Fig. 4. For a phase shift variation within the range of $-\pi$ to π, the output value changes from −8192 up to 8192. As can be seen from Fig. 4, the transfer function is strongly linear.

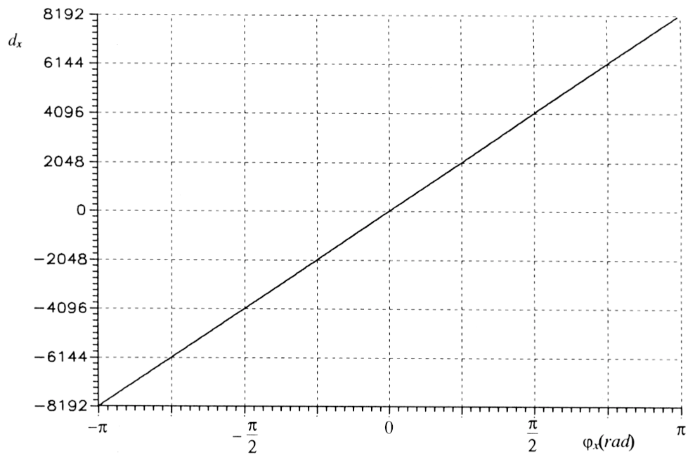

Fig. 4. Transfer function of the Phase-Meter

The measurement error in a digital domain is defined as:

$$R(d_{x0}, d_x) = d_x - d_{x0} \tag{32}$$

where d_{x0} is an ideal (exact) value of a referent phase-shift at the input of PM , and d_x is a measured value.

Phase shift, d_{x0}, is generated from a hardware which is identical to RPG, with resolution of 256 steps. According to the adopted values for M and K, (d_{FS} = 8192) the exact value of the input phase shift is determined as

$$d_{x0} = 64 d_{cx0} \tag{33}$$

where d_{cx0} represents a signed 8-bit integer.

Quantities d_{x0} and $R(d_{x0}, d_x)$ are determined by software.

The error function, wich corresponds to the transformation function, given in Figure 4, is sketched as a continuous line in Figure 5, while its approximation with polynomial of order 8 is sketched with dashed line. Error function is given for input signal of frequency *f*=125kHz. For the calibration of the Phase-Meter a value of $d_{cal} = \frac{15}{16} 2^{K-1}$ (=480) is used.

Vertical bars denote measuring subranges with respect to input quantity. Analysing the error function we can conclude the following:

- the largest error is R = 3, and with respect to the FS range it is equal to 0.036%
- the largest error exists at borders of measuring subranges. The error changes sign at transition from one subrange to another.
- The minimal error is obtained in the vicinity of the middle of the subrange, i.e. when the phase difference is small. Error in this case is R = ±1.

The error during calibration of T_{cal} is a direct consequence of finite ADC's resolution. Due to finite ADC's resolution, an error appears, which in a step of fine-phase-shift measurement is scaled. This assertion is practically proved by storing the error functions for the next two measurements. In the first case, the storing is performed for $d_{cal} = \frac{1}{2} 2^{K-1}$ (= 256). The diagram which corresponds to error function is given in Figure 6. By comparing Figure 5 and Figure 6, we notify an existence of larger measuring error and more pronounced periodicity within the measuring subrange. In spite of this, the total measuring error is less than 0.05%.

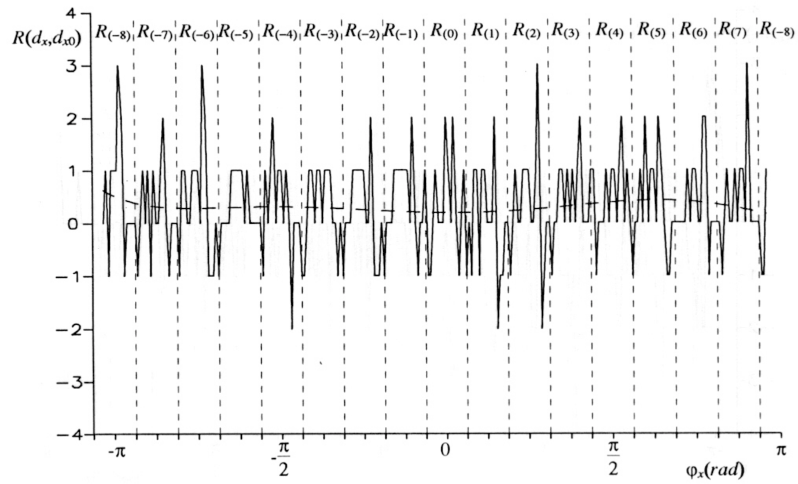

Fig. 5. Measurement error for d_{cal} = 256 calibration.

During the second measurement an effort was made to eliminate the error which is a direct consequence of uncertainty during determining T_{cal}. The calibration period is determined as:

$$T_{cal} = \frac{1}{2}(T_{cal+} + T_{cal-}) \tag{34}$$

where T_{cal+} and T_{cal-} are quantities that correspond to two different calibration periods.

The first calibration is performed when the procedure iterates from upper side, while the second iterates from bottom side. The error function is given in Figure 7. By analysing Figure 7 we conclude that the error magnitude is R = ±1, and it appears as a consequence of ADC's resolution.

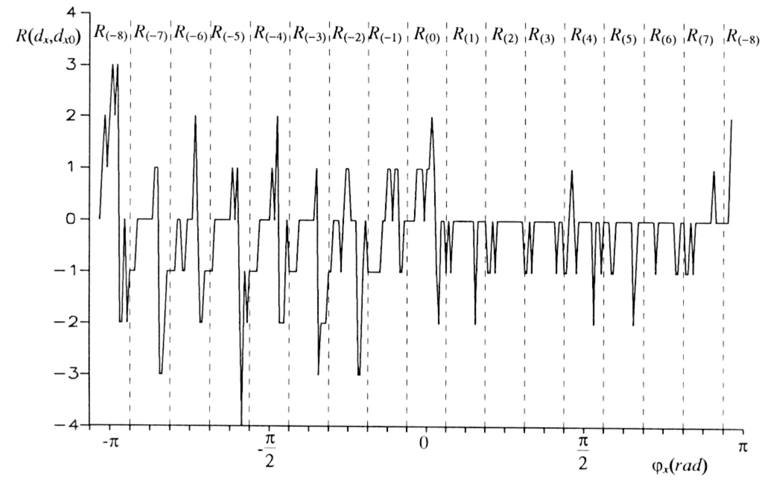

Fig. 6. Measurement error for d_{cal} = 480 calibration.

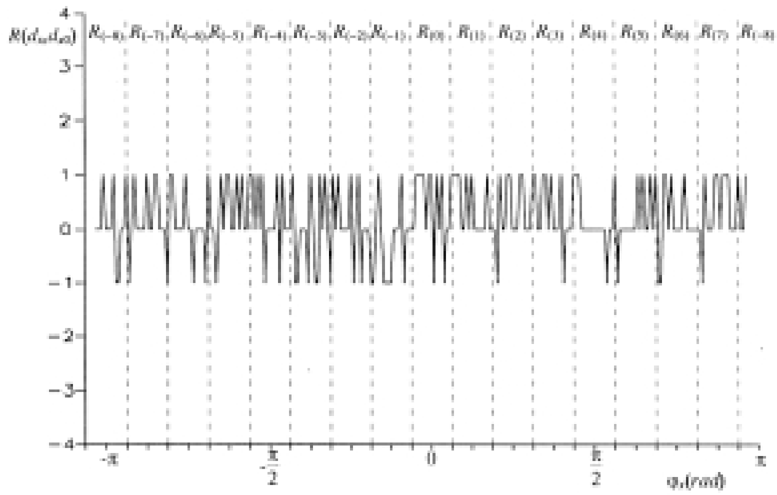

Fig. 7. Measurement error with two-fold calibration

Finaly we can conclude the following:

- The digital phase meter is optimal for implementation in industrial application.
- The phase shift meter is suitable for applications where 14-bits resolution is needed (in industrial application 12-bit resolution is standard).
- The phase shift quantum can be matched to measured units, i.e. to the number system in which the result is presented.
- There are no elements for manual adjustment.

7. CONCLUSION

In this paper a functional structure and principle of operation of a digital phase meter are described. The phase meter represents a building block of an embedded computer system intended for automatic measurement. The described method for phase shift measurement is implemented into the following three steps: autocalibration, coarse, and fine phase shift measurement. The experimental results indicate that the acuracy of the phase meter is within the range of its resolution. The phase meter is suitable for measurements in industrial applications.

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SISTEM ZA MERENJE FAZNE RAZLIKE NA BAZI UGRAĐENOG MIKRORAČUNARA

Branislav Petrović, Mile Stojčev

U ovom radu razmatrane su transformacije u oblasti domena podataka implementierane na digitalni merač fazne razlike kao sistem sa ugrađenim mikroračunarom. U radu je najpre razmatrana funkcionalna hardverska struktura sistema. Nakon toga opisani su algoritmi za autokalibraciju i grubo i fino merenje fazne razlike. Eksperimentalni rezultati pokazuju da je ostvarena 14 bitna rezolucija u frekventnom opsegu od 1 kHz do 500 kHz i da je ostvarena tačnost merenja bolja od 0,025 stepeni.