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REDUCTION OF GIBBS PHENOMENON IN EOG SIGNAL MEASUREMENT USING THE MODIFIED DIGITAL STOCHASTIC MEASUREMENT METHOD

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Abstract. *The method of digital stochastic measurement is based on stochastic analog-to-digital conversion, with a low-resolution A/D converters and accumulation. This method has been mainly tested and used for the measurement of stationary signals. This paper presents, analyses and discusses a simulation model development for an example of electrooculography (EOG) signal measurement in the time domain. Tests were carried out without adding a noise, and with adding a noise with various level of signal-to-noise ratio. For these values of signal-to-noise ratio, the mean and maximal relative errors are calculated and the significant influence of Gibbs phenomenon is noticed. In order to eliminate Gibbs phenomenon and decrease measurement error, a modified stochastic digital measurement method with overlapping measurement intervals has been developed and applied. On the basis of obtained results, the possibility of design and realization of an instrument with sufficient accuracy benefiting from the hardware simplicity of the method has been formulated. Also, the idea for the future research for developing a simulation model with a lower sampling frequency and implementing the proposed method is outlined.*

Key words: *Digital stochastic measurement, electrooculography, Gibbs phenomenon, signal processing, simulation model*

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1. INTRODUCTION

Nowadays, digital hardware components are used as a basis in realization of the modern measuring instruments, where measured time-continuous signals are previously conditioned. Then, conditioned signals are sampled, and converted into the digital variables. Throughout the process of an A/D conversion (ADC), the accuracy and speed are contradictory requests. Within the theory of measurements, and in the practice likewise, precise measurements of low-level, distorted and noisy signals are real challenge.

A possibility for reliable operation of instruments with inherent random error has been researched in [1]. The simple hardware and extremely quick operation of these instruments represent the fundamental characteristics of that approach. Adding a random uniform dither to ADC's input will decouple error from the input measuring signal, as shown in [2, 3]. This added dither suppresses the measurement error because of both A/D conversion and the additional external noise in the input signal.

For measuring average DC inputs, AC inputs and/or distorted AC inputs some specific methods are developed, based on this approach. They are known as digital stochastic measurement methods. Many prototypes of instruments, with extraordinarily low measurement uncertainty, are already realized [4-7].

In [6] an instrument, which has seven different input channels, is presented in detail. It enables performing the harmonic analyses, in each input channel, for the DC component and up to forty-nine harmonics (both sine and cosine components). Its hardware structure is designed for harmonic measurements, and the basis of its operation consists of stochastic A/D conversion and accumulation. The method, and also the expected measurement uncertainty, for 49 harmonics, with sampling frequency of 250 kHz per channel, are confirmed by simulation and experiments [6]. A digital stochastic measurement (DSM) method for various types of stationary signal has been explored and presented in [7]. Based on obtained results, it can be concluded that this method can be applied for measuring of any stationary signal. In the case of real power grid signals, when the fundamental frequency is drifted from its nominal value, the corrections of this method are necessary. The concrete improvement of this method is described in [8].

New approach of digital stochastic measurement method is presented and confirmed by simulations in [9]. The basis of the simulation approach is the technique of *Concurrent Programming*. In order to test the proposed methodology, for periodic input signals converted by the stochastic ADC, the discrete Fourier transform (DFT) has been applied. Achieved results prove that the Concurrent Programming technique increases only the simulation speed, and has no other effect on the measurement performance.

A concurrent computing technique for the DSM simulation acceleration is presented in [10]. The DSM presents a methodology that is used for an orthogonal transformation calculus/decomposition. In order to test the proposed methodology, power grid signals were harmonically analyzed through a DFT. A several levels of computing concurrency were used for harmonic decomposition. The main criterion was model accuracy, while the overall calculus speed was the parameter used for the simulation computing technique selection.

In the case of classical digital measurement of non-stationary signals, the measurement system may be exposed to the high-level ambient noise (where the signal-to-noise ratio may be extraordinarily low). Therefore, the techniques of conditioning will not be satisfactory. The results of alternative solutions research for situations of the high-level ambient noise presence are presented in [11, 12]. In these papers the implementation of the DSM approach in non-stationary signal harmonics' measurement, with different measurement time is also described.

In [11] the EEG signal is selected as an example of a real non-stationary signal, and measurement uncertainty is calculated by the developed theory. In papers [11, 12] the DSM measurement of harmonics of the EEG signal is tested by simulations and experiments. Theory calculations are compared with the results of simulations and experiments that are carried out. By increasing the sampling rate of the used A/D converter, the presented method provides a decrease of the measurement uncertainty, even at low *SNR* values.

The implementation of the DSM method for the EEG signal measurement in time domain is presented in [13,14]. The measurement error increased, as a consequence of the Gibbs phenomenon. It is shown that the average maximal error relative to the range of input signal is decreased when the measurement interval is extended from 20 ms to 2 s.

Biomedical signals are very weak signals and high-level ambient noise may exert significant influence on their amplitude, which leads to incorrect measurement results. In this paper the application of the modified method for measuring such a noisy biomedical signal, where an EOG signal is used as the example, is described in detail.

The retina resting potential measurement technique is named electrooculography (EOG). The resulting signal is known as electrooculogram. In the function of time, EOG signal presents the corresponding record of the distinction in electrical charge between the front and back of the eye for every kind of eyeballs movements, such as up, down, left, right, and eye blinking [14]. This record is obtained by electrodes that are placed on the skin near the eyes.

Obtained recorded signals may be used for external devices control, like electric wheelchairs, virtual keyboards, artificial arms and robots. Also, the recordings of eye movements are necessary in ophthalmology for a detailed description and analysis of the eye motoric functioning. Numerous changes in the eye may be detected by analysing EOG signals. Therefore, the condition of the eye may be determined.

2. Review of the Digital Stochastic Measurement Method

The DSM method is based on measurement over an interval. Measurements are carried out with a low- resolution ADCs and accumulators (ACC). In order to eliminate the influence of the quantization error, which is significant here, the white noise h_1 (dither) with a uniform amplitude distribution is added to the linearly amplified input signal $y_1(t)$, in the range of quant of the applied ADC. The dither has been assumed to be the sum of all noise values that were not discarded before the input of the DSM block.

The method of digital stochastic measurement is based on the stochastic analog-to-digital conversion, with a low-resolution A/D converters and accumulation.

If needed to measure the integral (the mean value, $\bar{\Psi}$) of a product of two signals, Ψ, [4], then the measurement block has two uncorrelated dithers h_1 and h_2 added to input signals $y(t)$ and $y_a(t)$, respectively (Fig. 1*a*). The values Ψ_e and Ψ_a present the sampled values of the dithered input signal $y(t)$ and dithered input signal $y_a(t)$ within time interval (T), respectively. Dither signals h_1 and h_2 are random signals with a uniform amplitude distribution. Accumulator is realized as an *up-down* counter, and the ratio of the accumulator value and the number of samples gives the mean value of the input signal. In [7] it was shown that the DSM method can be used for measuring the coefficient of the orthonormal expansion. In that case, the second channel has been replaced with the memory block (Fig.

1*b*), which stores the digitized dithered basis (cosine or sine) function $y_{ad}(t) = y_a(t) + h_2$. Thus, the equation $y_a = R \cdot \cos k\omega_0 t$ is valid for measuring the k^{th} cosine Fourier coefficient, i.e. the equation $y_a = R \cdot \sin k\omega_0 t$ for measuring the k^{th} sine Fourier coefficient.

Here, the values Ψ_e and Ψ_a present the sampled values of the dithered input signal $y(t)$ and dithered basis function $y_a(t)$ within time interval (T), respectively. In order to measure M coefficients this structure is implemented in a parallel (Fig. 1*c*), where each coefficient is measured as shown in Fig. 1*b*.

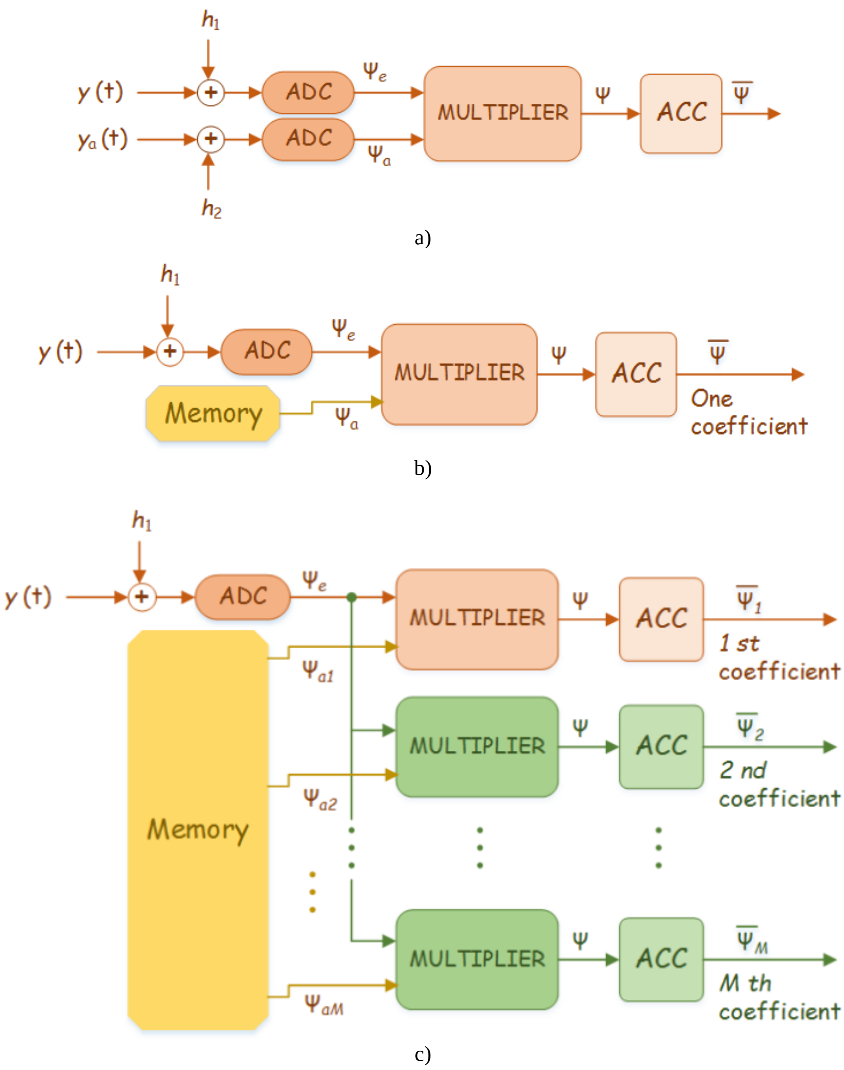

Fig. 1 Stochastic measurement, based on A/D conversion (*ADC*) and accumulation (*ACC*), of: a) the mean value $\overline{\Psi}$ of a product of two signals, b) one coefficient of the orthonormal expansion, c) M coefficients of the orthonormal expansion

The digital stochastic measurement system consists of three blocks: a block for signal conditioning (amplification, linearization, filtering, level adjustment, noise suppression, electrical isolation), a block for digital stochastic measurement and a block for data processing, recording and displaying. The system was implemented using the Matlab software package. Conditioned signal is an input signal of a DSM block. The outputs of the DSM block are the Fourier coefficients, where each Fourier coefficient is a function of all analog input signal samples over the entire measurement interval. The measurement result is a set of harmonics, which can be the input for calculating digital values of signals in the time domain.

3. Input Signal and Simulation Model

The DSM block input signal is a conditioned EOG signal. Typical EOG signals have amplitudes in the range of mV with a frequency of DC component of 100 Hz [15]. The EOG signal is one of the standard biopotential that is measured during deep sleep, or during the so-called *REM* (Rapid-Eye-Movement) sleep phase. The *REM* phase involves very fast and random eye movements. In a normal night's sleep, the *REM* phase occurs every 90 minutes and lasts 5 to 30 minutes continuously.

Aiming to obtain correct simulation results, which we can later compare with each other, the same EOG signal was used for each simulation. The repeatability of the EOG signal cannot be achieved by measurement on a human subject, and real "live" measurements for each cycle of simulation and experiment. For this reason, the source of the input EOG signal in the simulation measurements was not a human subject, but a digital data source of conditioned signals that was made from records previously measured by standard EOG measurement instrument [16, 17]. The DSM block input signal represents the signal extracted from a real measurement session of the EOG signal (period of 10 s downloaded from PhysioNet [16]), and is shown in Fig. 2. The range of this signal is from -0,43 mV to 0,35 mV.

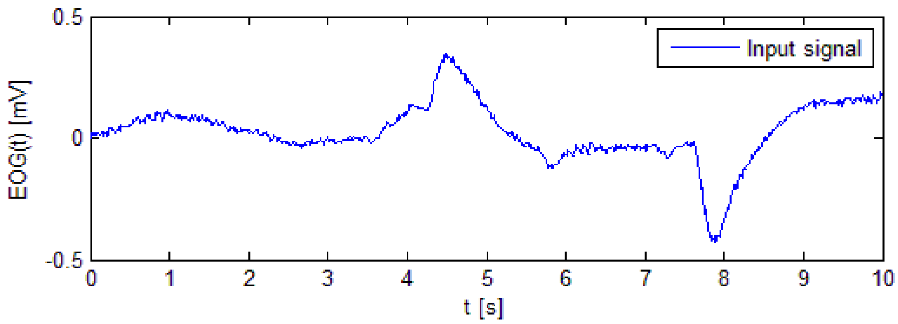

Fig. 2 Input signal – 10 s extracted from real measurement session of EOG signal

Given that amplification and level transition are common procedures for signal conditioning, these signal values are amplified 1000 times and superimposed with 0,025 V. Therefore, the conditioned EOG signal is the input of the DSM block. In preparatory real measurement (which was a typical digital measurement procedure), the EOG signal was stored with 250 samples per second (S/s). To obtain a smoother input, or less stepped signal, these 250 S / s records were transformed into 5000 S / s data. For resampling input signal by an integer factor, with a given value of 20, the *Matlab* function *'interp'* has been used. Each sample is stored as a 64-bit floating point value.

4. Simulation Model for EOG Signal Measurement by DSM Method

The simulation model has been realized using the software package Matlab. The DSM block was configured according to the data presented in Table 1.

Four sets of 100 simulations (4 x 100) were run - one set of 100 simulations without adding noise and the other three sets of 100 simulations with the addition of white noise to the input signal. The added noise had an uniform probability density function, and the signal-to-noise ratio (*SNR*) was 10 dB, 0 dB, and −10 dB, respectively. It was assumed that there were no anti-aliasing (analog low-frequency) filters before block for the DSM, which would limit the frequency range of noise at the input. On the one hand, the absence of an anti-aliasing filter before the DSM block is inconvenient from the noise level entering the digitization block, but on the other hand, this is better from the point of view of the size and optimization of the conditioning block due to the reduction in the number of components.

Table 1 DSM block properties

Number of measurements	4 x100 (without noise added and for each level of *SNR*)
SNR level	Without adding noise, 10 dB, 0 dB, -10 dB
A/D converter	Resolution: $m_1 = 6$ bits Input range: $\pm R$ and R = 2,5 V Sampling frequency: f_{ADC} = 250 kHz
Measurement interval	$[0,T]$, $T \in$ {0.1 s; 0.2 s; 0.5 s; 1 s; 2 s}
Fundamental frequency	$f_0 \in$ {10 Hz; 5 Hz; 2 Hz; 1 Hz; 0.5 Hz}
Number of samples per measurement interval	$N = f_{ADC} \cdot T \rightarrow N \in$ {25000; 50000; 125000; 250000; 500000}
Digital dithered base functions stored in memory	Simulating an ADC with properties: Resolution: $m_2 = 8$ bits Range: $\pm R$ and R=2,5V Sampling frequency: f_{ADC} = 250 kHz
Number of measured coefficients	DC component + 15 sine coefficients + 15 cosine coefficients

The final result of one set of simulations, in the time domain, is calculated as average of the results of all simulations in that set. Therefore, at the end of each measurement series, the reproduced signal is obtained as a result. After completing the entire simulation process, measurement errors (maximum absolute error, maximum relative error in relation to the input signal range, mean absolute error, mean relative error in relation to the input signal range) in the frequency and time domains are obtained, as well as the corresponding graphs of the input and reproduced signal. Absolute error presents the absolute value of the difference in the measured (obtained by DSMM) and actual (input signal) value of the signal, and relative error is the ratio of the absolute error to the actual value, expressed in percentages. For each measurement interval, from 0,1 s to 2 s, two groups of sets of simulations were carried out, for

15 and 25 harmonics, respectively. So, the total number of simulations that are done is 4000 (5 measurement intervals, 2 different harmonic numbers, 4 sets of 100 simulations each).

After analyzing the obtained results, with various lenght of measurement intervals and various number of harmonics, we concluded that the best results are obtained for a measurement interval of 0,5 s and 15 harmonics. Measurement errors in the time domain are shown in Table 2. The duration of the simulation in this case is 107,5 s.

Table 2 Measurement errors in time domain for measuring interval of 0,5 s

ERRORS	No noise added	*SNR* 10 dB	*SNR* 0 dB	*SNR* -10 dB
Max absolute [mV]	0.5469	0.5456	0.5505	0.5221
Max relative [%]	27.2708	27.2056	27.4527	26.0380
Mean absolute [mV]	0.0137	0.0138	0.0145	0.0208
Mean relative [%]	0.6857	0.6893	0.7212	1.0396

The corresponding graphs, which represent the comparison between the input and the reproduced signals, for the measurement interval of 0,5 s and different SNR values, are presented in Fig. 3 to Fig. 6.

Enlarged graphics, shown in Fig. 3 to Fig. 6, are presented in Fig. 7 to Fig. 10.

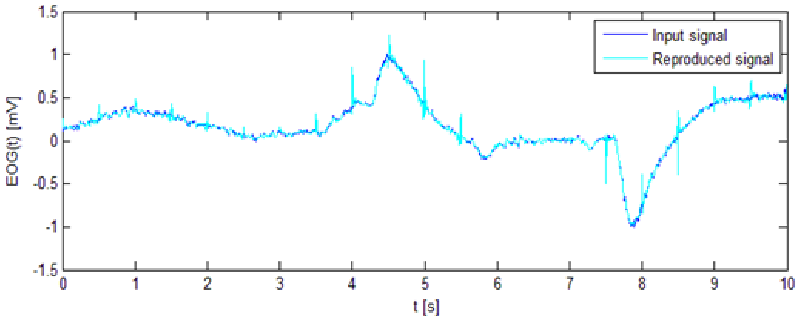

Fig. 3 Graphical presentation of input and reproduced signals - *no noise added*.

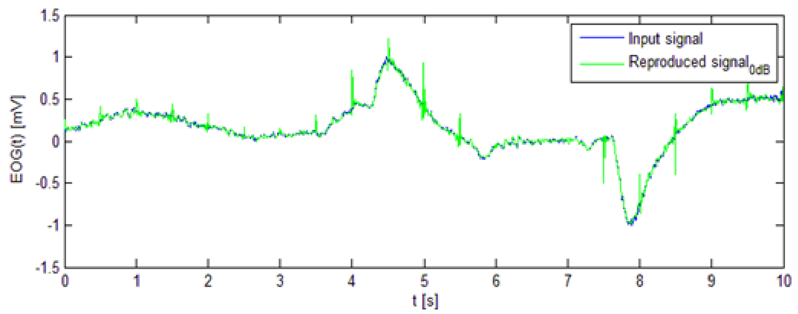

Fig. 4 Graphical presentation of input and reproduced signals - *SNR* = 10 dB

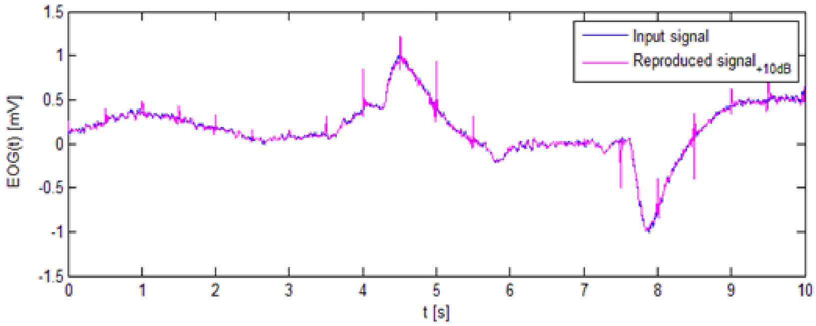

Fig. 5 Graphical presentation of input and reproduced signals - *SNR* = 0 dB

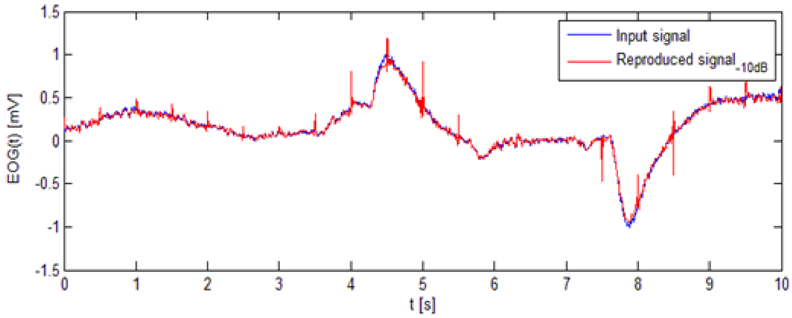

Fig. 6 Graphical presentation of input and reproduced signals - *SNR* = -10 dB

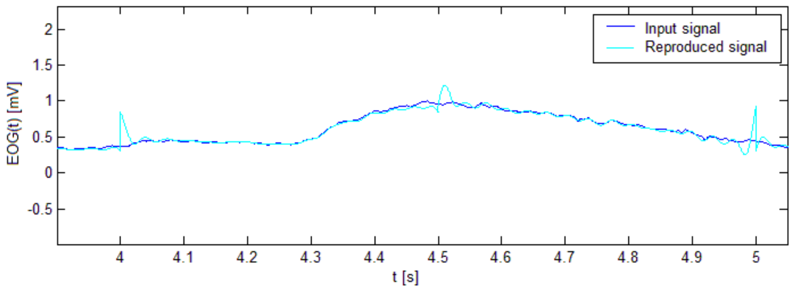

Fig. 7 Zoomed graphics from Fig. 3.

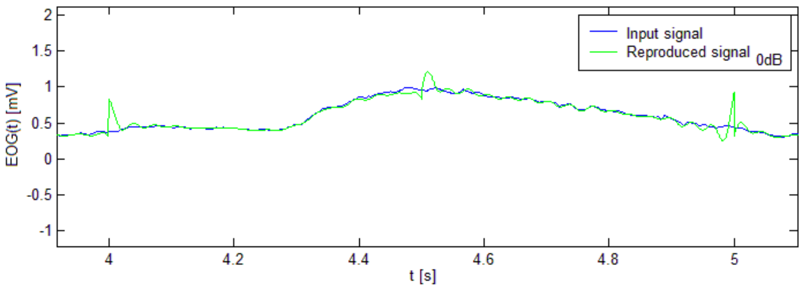

Fig. 8 Zoomed graphics from Fig. 4.

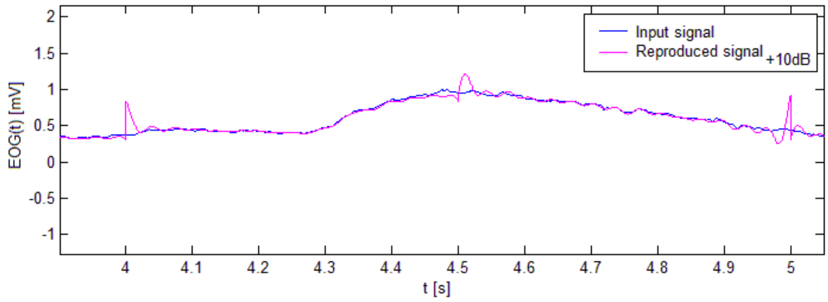

Fig. 9 Zoomed graphics from Fig. 5.

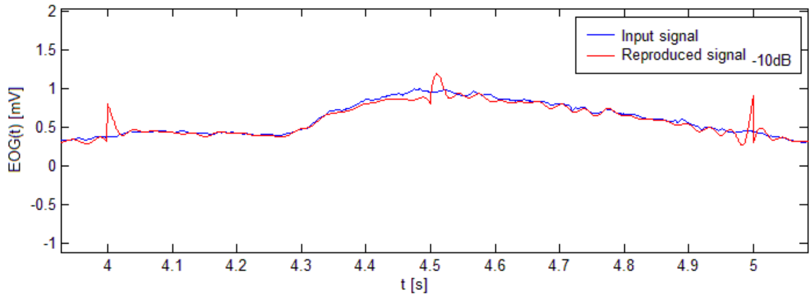

Fig. 10 Zoomed graphics from Fig. 6.

Significant deviations of the reproduced signal relative to the input signal can be observed at the beginning and at the end of each measurement interval, i.e. every 0,5 s. They are a consequence of the occurrence of the Gibbs phenomenon [18-21]. This phenomenon significantly increases the measurement error. For SNR 0 dB the maximum relative error reaches as high as 27,45%.

As it is known, the Gibbs phenomenon [18, 19] is the unique manner in which the Fourier series of a piecewise continuously differentiable periodic function behaves at a jump discontinuity. Namely, the n^{th} partial sum of the Fourier series has large oscillations near the jump, which increases the maximum of the partial sum, and that overshoot does not decrease as n increases [19-21].

If the DSM approach is implemented and if there is a discontinuity between the first and the last analog sample over a measurement interval the measurement error is increased, and the reason of increasing layed in the Gibbs phenomenon appearance. This relatively high error appears at the edges of the measurement interval (at the places of the discontinuity) and it can be explained by the Gibbs phenomenon.

5. Development of Modified DSM Method

Since the influence of the Gibbs phenomenon on the measurement error is significant, the idea of modifying the digital stochastic measurement method has appeared. The modification is to achieve the overlap of the measurement intervals (time windows) T_k. For this purpose, an identical measuring channel that measures the same EOG signal, but measurement begins with a defined delay dT, was implemented. In this paper, the delay dT is defined as dT = T/4.

Fig. 11 shows the overlap of the measurement intervals T_k and T'_k (k = 1, 2, ...), which represent the measurement intervals in the measuring channels $Ch1$ and $Ch2$, respectively. The gray parts of the measurement intervals represent areas where the Gibbs phenomenon occurs, while the white parts indicate areas where the Gibbs phenomenon does not exist.

As a final result, the resulting signal is obtained by taking from each measurement channel only samples from the white parts of the overlaped intervals (dashed line). Fig. 12 shows the final result of overlapping measurement intervals and getting the resulting signal. This method can be named the modified digital stochastic measurement method (MDSMM).

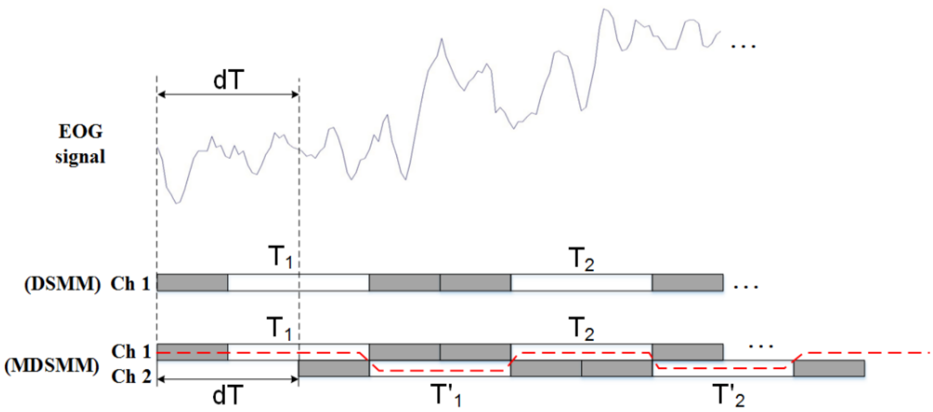

Fig. 11 Graphical presentation of measurement intervals overlapping.

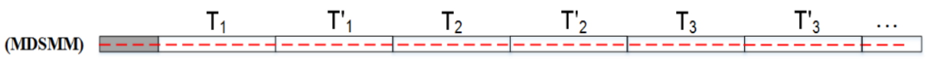

Fig. 12 Graphical presentation of resulting signal obtaining.

After completing the entire simulation process, the results are measurement errors in the time domain (maximum absolute error, maximum relative error in relation to the input signal range, mean absolute error, mean relative error in relation to the input signal range), as well as the corresponding graphs of the input signal, the reproduced signals for each measurement channel, and the resulting signal. Here, the absolute error presents the absolute value of the difference in the measured (obtained by MDSMM) and actual (input signal) value of the signal, and relative error is the ratio of the absolute error to the actual value, expressed in percentages.

The comparisons between the input and the resulting signals, obtained by MDSM method for various SNR levels, are presented in Fig. 13 to Fig. 16, respectively. Also, the comparisons between the input and the resulting signals, obtained by classical measurement method for various SNR levels, are presented in Fig. 17 to Fig. 20, respectively.

A comparative overview of the time domain measurement errors for both measurement methods, as well as for the classical digital measurement method for measuring intervals of 0,5 s and 15 harmonics, are presented in Table 3.

The duration of the simulation in the case of the proposed novel method is 370,78 s, which is significantly longer than the simulation for measuring the EOG signal by the DSM method. The reason for such a long duration of the simulation lies in the fact that in the case of overlapping time windows, it is necessary to make twice as many measurements of the Fourier coefficients and to merge the two reproduced signals into the resulting signal. This requires a large number of calculations, as well as a large memory space.

Table 3 Comparative view of measurement errors obtained by classical measurement method, by DSM method and by MDSM method

ERRORS	Classical digital measurement	DSMM	MDSMM
	No noise added		
Max absolute [mV]	0.0308	0.5469	0.0542
Max relative [%]	3.9589	27.2708	2.7013
Mean absolute [mV]	0.0165	0.0137	0.0063
Mean relative [%]	2.1277	0.6857	0.3117
	SNR level: +10 dB		
Max absolute [mV]	0.0183	0.5456	0.0528
Max relative [%]	2.3588	27.2056	2.6350
Mean absolute [mV]	0.0034	0.0138	0.0063
Mean relative [%]	0.4359	0.6893	0.3146
	SNR level: 0 dB		
Max absolute [mV]	0.0442	0.5505	0.0572
Max relative [%]	5.6804	27.4527	2.8516
Mean absolute [mV]	0.0098	0.0145	0.0070
Mean relative [%]	1.2654	0.7212	0.3511
	SNR level: -10 dB		
Max absolute [mV]	0.1479	0.5221	0.0922
Max relative [%]	19.0183	26.0380	4.5955
Mean absolute [mV]	0.0313	0.0208	0.0144
Mean relative [%]	4.0225	1.0396	0.7157

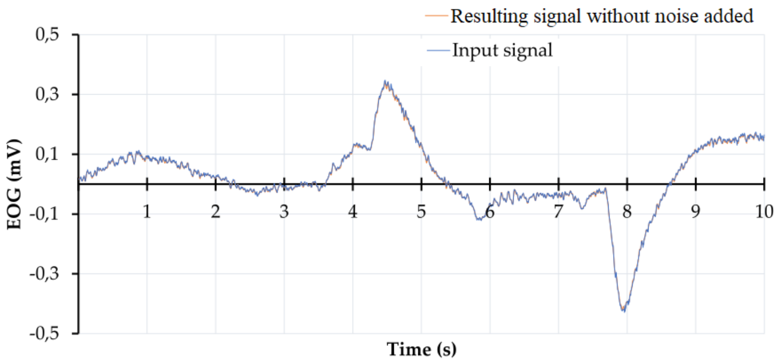

Fig. 13 *MDSM method*: Presentation of input and resulting signal without noise added.

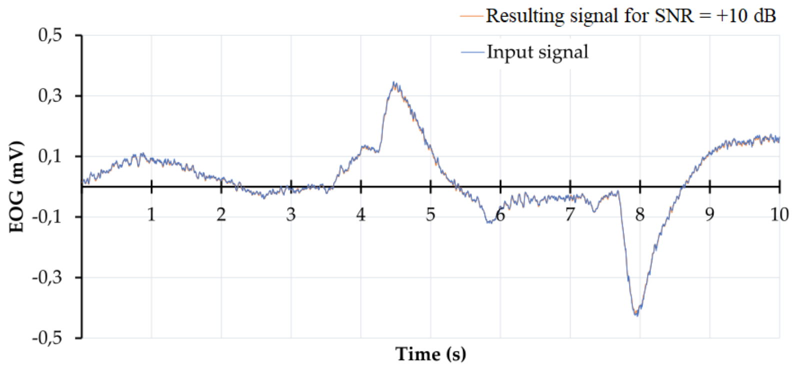

Fig. 14 *MDSM method*: Presentation of input and resulting signal with *SNR* = +10 dB.

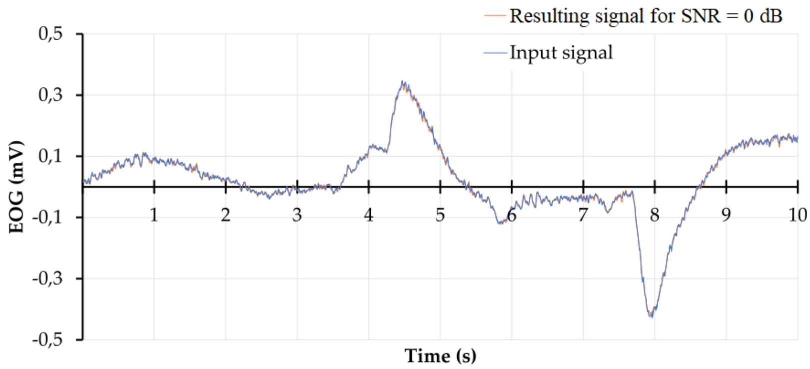

Fig. 15 *MDSM method*: Presentation of input and resulting signal with *SNR* = 0 dB.

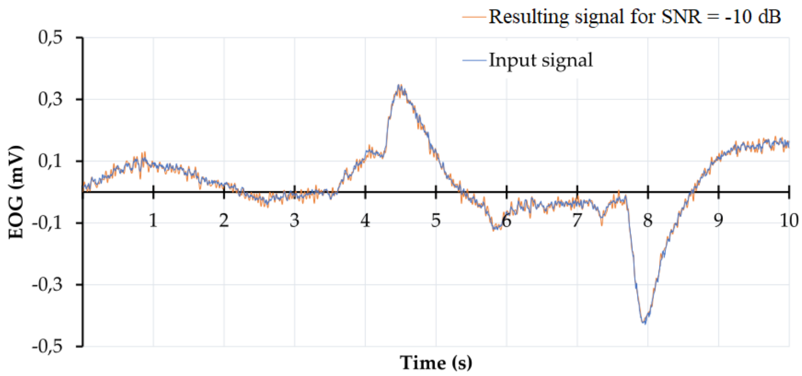

Fig. 16 *MDSM method*: Presentation of input and resulting signal with *SNR* = -10 dB.

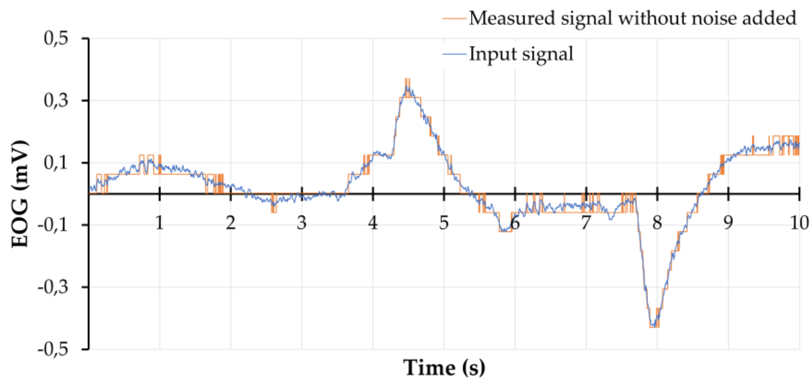

Fig. 17 *Classical method*: Presentation of input and measured signal without noise added.

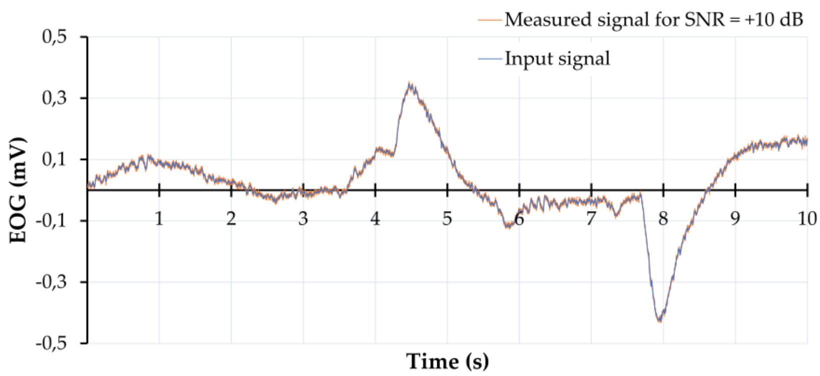

Fig. 18 *Classical method*: Presentation of input and measured signal with *SNR* = +10 dB.

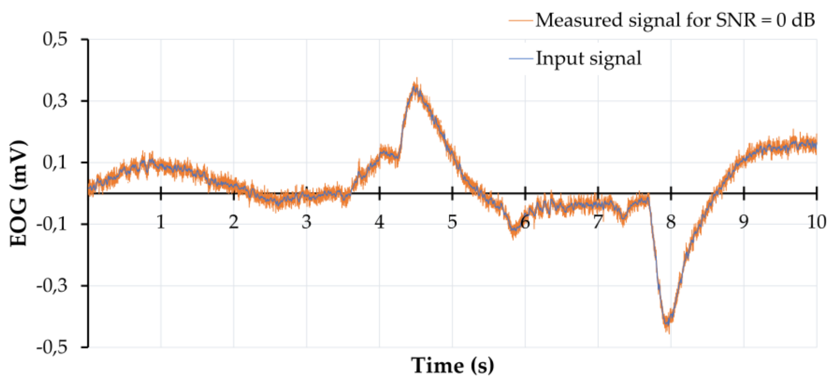

Fig. 19 *Classical method*: Presentation of input and measured signal with *SNR* = 0 dB.

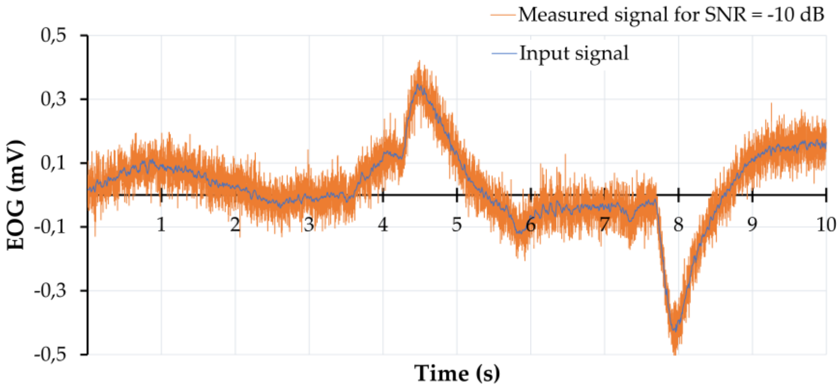

Fig. 20 *Classical method*: Presentation of input and measured signal with *SNR* = -10 dB.

5. Conclusion

This paper presents a simulation model development for digital stochastic measurement of EOG signal in the time domain, emphasizing the problem of the influence of the Gibbs phenomenon on measurement errors. The realization of DSM block is carried out by 6-bit and 8-bit A/D converters. Tests were carried out without adding a noise, and with adding a noise with various level of signal-to-noise ratio (SNR): 10 dB, 0 dB, and −10 dB. The achieved mean relative error is 1,04 % and maximal relative error is 26,04 %, when SNR level is -10 dB. The corresponding plots of the input signal and achieved reproduced signals are presented for each set of simulations.

Based on results, it can be concluded that the Gibbs phenomenon that occurred at the ends of each measurement interval has the greatest influence on the measurement errors. A new method, with overlapping measurement intervals, has been developed in order to eliminate Gibbs phenomenon and decrease the measurement error. Thus, in the worst case, i.e. when SNR is -10 dB, the obtained mean relative error and maximal relative error are decreased, down to 0,72% and 4,6%, respectively. Considering these results, the suggested approach can be used for design and realization of an instrument with sufficient accuracy, benefiting from the hardware simplicity of the method.

The duration of the simulation in the case of the proposed novel method is significantly longer than the simulation for measuring the EOG signal by the DSM method. Therefore, it is concluded that the frequency of 250 kHz is unsatisfactory from the aspect of practical realization of the proposed model for digital stochastic measurement of the EOG signal. The idea for the future research is to develop a simulation model with a lower sampling frequency and implement the proposed method.

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