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## PHONOCARDIOSIGNAL AS A PERIODICALLY CORRELATED STOCHASTIC PROCESS PREPROCESSING ALGORITHM STRUCTURE GROUNDING

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**Summary.** For the cardiovascular disease early diagnosis by the remote monitoring systems the fonokardiosyhnal (as periodically correlated random process) simultaneously registered with electrocardiosignal usage is proposed. An registered signal preprocessing procedure, groundet in this article, is carried out by the following algorithm: detrending procedure (the constant component of the signal (trend) reducing), smoothing (high noise suppression with minimal spectrum distortion and P-peacs offset locations), the P-peacs repeating intervals determination.

**Key words:** biosignal, cardiosignal, phonocardiogram, mathematical model, simulation model, verification, heart pathology detecting algorithms, MATLAB.

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**Statement of the problem.** The cardiovascular system (CVS) state is the key integral indicator used to evaluate human health, To CVS pathological processes at an early stage of it progression identify in time diagnostic CVS state monitoring systems which would be able to easily integrate into the Ukrainian social and infrastructural realities development is very relevant [1]. The basis for such systems creating is appropriate programm and mathematical software that would allow to find informative and invariant biosignal signs which could be used for heart state diagnostic and are understandable and acceptable for physicians [2].

**Analysis of the available investigations.** The up-to-date diagnostic systems widely use the polycardiogram method [3] based on synchronously registered electrocardiogram (ECG), a phonocardiograph (FCG) and a sphygmogram (SG). The complete information about cardiovascular system state can be obtained only if several diagnosing methods are used simultaneously. In a number of scientific authors's works (M.A Kurshakov, P.E. Lukomsky, S.A. Lupenko, A.A. Selidovkina) is emphasized the advantages on such comprehensive approach. The work of most modern cardio-diagnostic systems («CARDIO +», «REOCOM Professional») is based on the various physical nature signals processing separately. The phonocardiosignal most completely represents a CVS activity as hemodynamic one and is an information carrier about its state in the terms of system and signal concept. In general, approaches to PCS processing could be divided into deterministic (spectral decompositions, in different basis decompositions) and stochastic. In particular, in the G.M. Osukhivska works for the tone signal processing (in compare to the PCS the heart tones range frequency is localized below the noise frequency range, and the tone energy is much higher than the murmurs energy), the concept of «relaxational multipulser» is introduced and the filter statistical method is applied using the stochastic signals energy theory (ETSS). Another approach to the cardiosignal representation in a form of finite-dimensional vector's coordinates superposition of cyclic rhythmically related random processes for as synchronously registered cardiosignals (SRCS) mathematical models is given in S.A Lupenko works [4, 5]. Since SRCS statistical processing is carried out based on the signal rhythmic structure (rhythm function), as input data in such processing are the signal values, the discrete rhythm function, the number of signal's cycles and the number of zones it consists in each

cycle [4, 5]. This requires data sequences resampling and interpolation causing a significant amount of hardware and software resources usation, which is not suitable for smart wears (smart clothes) patient bio-indicators remote monitoring systems in a compact form factor.

The quality of the PCS processing is determined by its mathematical representation method [6] – the PCS mathematical model as a periodically correlated stochastic process (PCSP) of  $\pi^T$ , class was previously grounded [7, 8]. Such model has the means to combine the randomness with repetition properties in its structure, interpreting as a probability characteristics periodicity and determinisity the methods (synphase, component, filtering [9]) fore researched object processing and the polycardiogram CVS state diagnosing telemetry systems design.

**The Objective of the work** is the PCS synchronously registered with ECS as periodically correlation stochastic process preprocessing for the noise impact minimization.

**Statement of the task.** The PCS synchronously registered with ECS preprocessing taking into account its genesis mechanism for the noise impact minimization.

**Experimental model.** The algorithms for synphase method realization [10] can be integrated into modern computer diagnostic instruments, and its advantage over other methods is the number of hardware and computing resources reducing. The PCSP as a FCS model using allowed to consider the NERVOUS REGULATION influence (sinus node as a «rhythm driver»), detect changes in the heart ACTIVITY on the early disease stages by introducing a new informative invariant characteristics class – the spectral components obtained as a result of synphase method signal processing.

However, the synphase method requires the statistical material homogeneity which complicates the researches and the input sequence autocorrelation function period value detection, which in the PCS case, can be represented as heart duration mean value.

The autocorrelation function period value detection classic approach the autocorrelation function repetition period detection [2]. This method is sensitive to the input sequence length and the heart cycle phase structure, which makes it impossible to ensure the results repeatability. The heart rate variability (HRV) is traditionally estimated about by the ECG RR-intervals duration, although it is advisable to consider the PP-intervals duration, since the exatly P-wave [11] is the beginning of a new heart cycle excitation originates in the sinoatrial (SA) node. The prevalence of RR-intervals estimating is due to the fact that the R-wave, especially in the second standard lead, is easiest to allocate from the electrocardiosignal during signal processing because it amplitude is the biggest one. For HRV registration there can be used not only ECG but some other methods for heart rate recording (rheography, plethysmography, the major arteries Doppler ultrasound, echocardiography, phonocardiography). Therefore, it is proposed to use an PP-interval value for every single heart cycle duration value detection, since the P-wave corresponds to the moment of the action potential (Schmidt-Voigt) activation. In order to further PCS usage in the remote monitoring systems [12] of the CVS state diagnostics at early disease stages, it is suggested to choose the PCSP as FCS model [7, 8] (since this model is adequate to the signal genesis nature) and the synphase processing method.

PCS as the CVS functional state data carrier also contains undesirable artefacts in particular: noises which emerge during the PCS registration (microphone displacement on the skin surface, the phonocardiograph contact bounce, external noises in an examination room); patient's body endogenous (respiration, intestinal peristalsis); phonocardiograph zero drift (trend). PCS preprocessing [13] is proposed to be carried out according to the following algorithm: signal detrending (trend and signal constant component elimination), smoothing (high-frequency noise reducing with minimal spectrum distortion and minimal P-wave location displacement), the P-wave repeatability period finding.

The trend minimization classic approach [14] is a two-stage process applying. On the first stage, the sequence approximation is performed, for example, using  $n$ -th order Newton's polynomial. And on the second one, an calculated sequence from the signal and trend mixture additive subtraction (detrrending) using the same  $k$ -th polynomial length, where  $k < n$ . However, in the FCS case where there are at least a breathing trend and parasitic 50 Hz component (network frequency) are present, the method is unsuitable because it does not allow eliminate both of these components simultaneously. In practice, a sequence of a high-frequency (HF) and notch filters are used in analogue electronics devices to, respectively, trend, constant signal component and 50 Hz power supply network impact on the cardiograph leads reducing. In our case, the synphase method is insensitive to the coherent components present in the signal, so there is no need to impacts elimination.

Since the developed algorithm is focused on its application in the patient's CVS state remote monitoring systems, so in order to trend minimization, it is proposed to use the hardware implementation the high-pass Bessel filter (Sallen-Key topology) implementation, which has uniform (flat) amplitude-frequency response characteristics (AFR) (minimal equiripple in passband), linear phase-frequency characteristic (PFR), and the constant group delay.

Throughout the bandwidth, the analogue Bessel filters are characterized by a almost constant group delay. This allows to save the signal shape passing through such a linear system, on condition that their spectrum is located in the filter bandwidth. Bessel's Discrete Filters do not have this property. The designed Bessel filter order is chosen according to an empirically formulated criterion [13]:

$$K=(n \cdot (\frac{K_{f_1} \cdot f_s}{\Delta})) < 0,3, \tag{1.1}$$

of where  $n$  – the filter order;  $K_{f_1}$  – the coefficient of attenuation at a 1 Hz frequency, times;  $f_s$  – the coefficient attenuation at cutoff frequency;  $\Delta = f_s - 1$ .

A 3-rd order filter with a cutoff frequency of 10 Hz with AFR and the PFR shown on the Figure 1 was synthesized as the result of choosing.

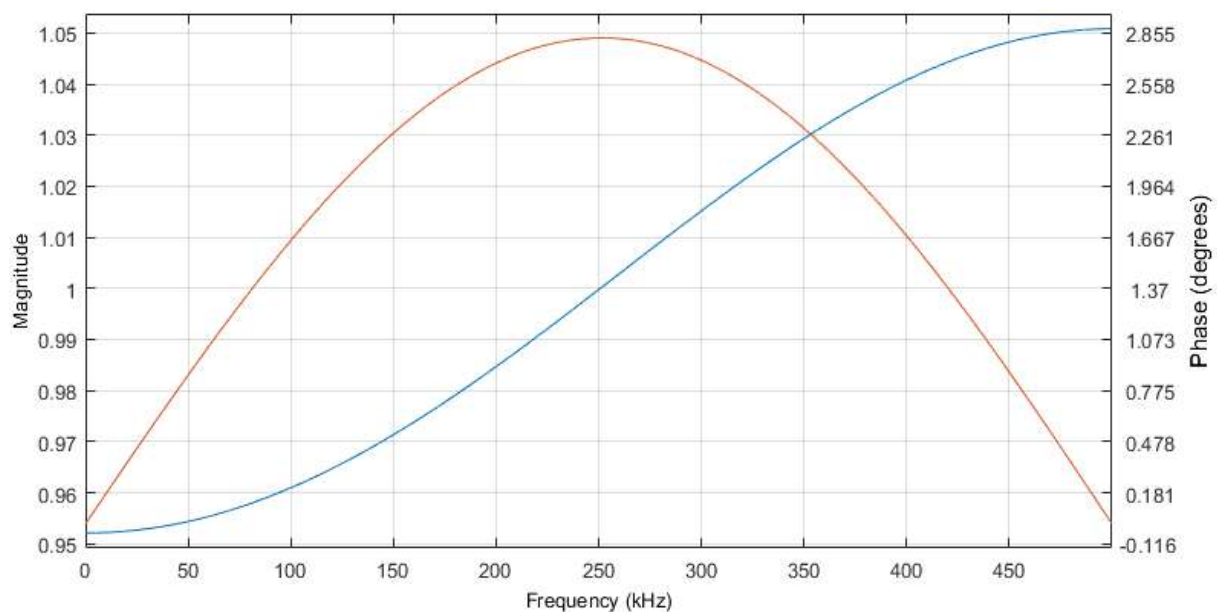
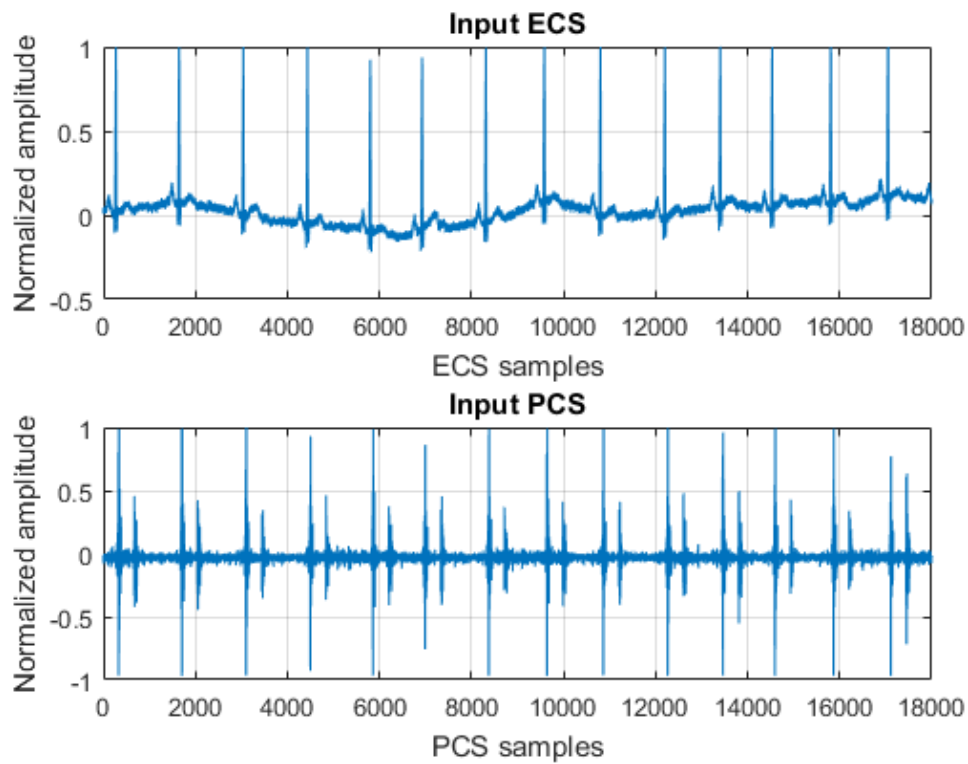


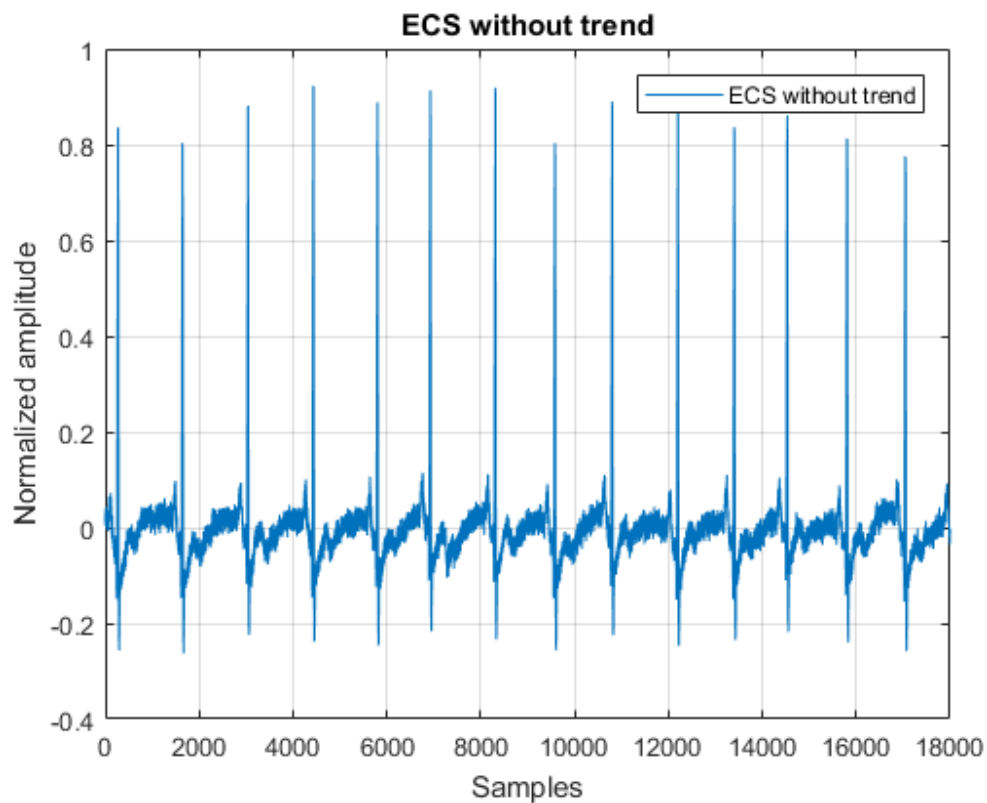
Figure 1. AFR and PFR of filter, synthesized in Matlab environment

The input signal (synchronously registered FCS and ECS) has the form:



**Figure 2.** The input signal – synchronously registered FCS and ECS

ECS filtered by using hardware (without trend) has the form:



**Figure 3.** ECS without trend

The next step is the R-waves location finding «on the fly» by the threshold method.

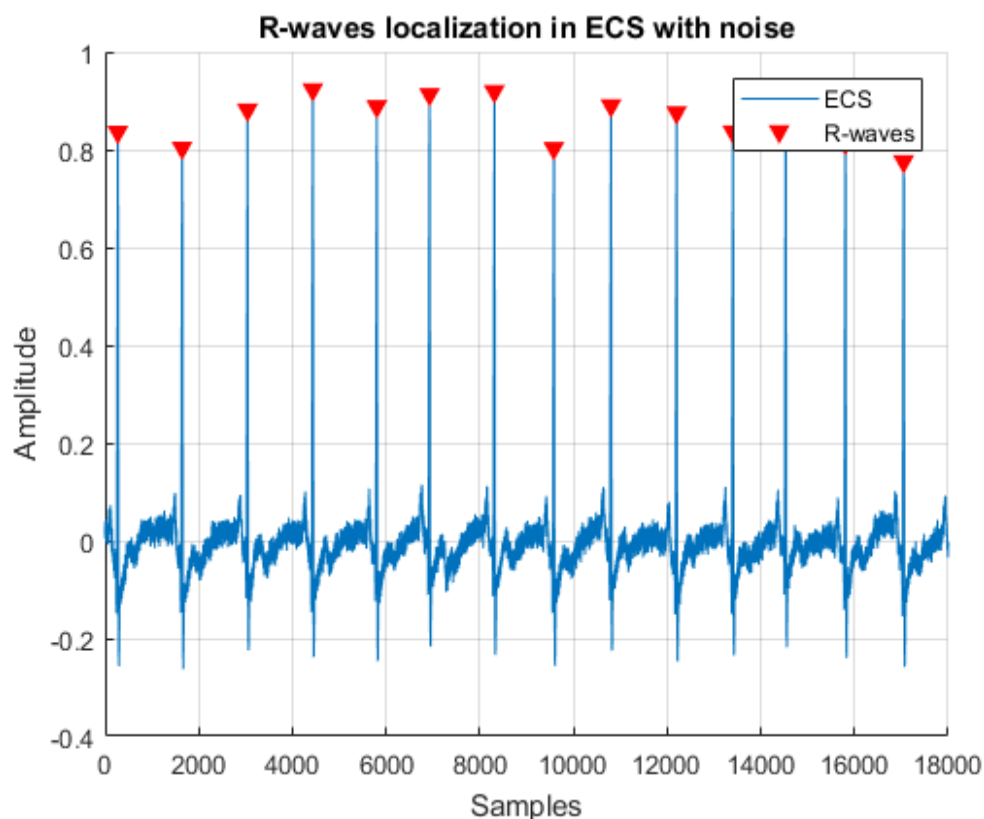


Figure 4. R-waves localization in ECS

Based on Slutsky's rule that the dynamic system after disturbance asymptotically approaches the new balance state, the PCS is registered and processed only on the organism homeostasis condition – the RR-interval varies with an absolute deviation of 5%, it means that the heart rate is relatively stable.

In order to reduce the computational resources and based on the equations grounded by V.L. Karpman, P-wave is not searched at the entire RR-interval, but in the range of its possible localization.

Since the P-wave is much smaller than the R one and its shape is more smooth, it is more distorted under the high-frequency noise impact. To find correctly maximums localization with high accuracy on low signal to noise ratio values condition is problematic. The low frequency filters usage is unacceptable, since they, in addition to phase distortions, cause strong sharp waves shape distortion and shifted them in time (strongly distort signals having discontinuity of the first kind).

In our case, a high-frequency noise is uncorrelated with a significant signal.

Then it is advisable to use smoothing methods. One of the most commonly used techniques used for signals processing in many industries [16] is different kinds of moving average methods. In the general case, the moving average is numerically equal to input sequence arithmetic average at the specified range. The method of the modified moving average is a recurrence ratio, for which each subsequent value of the filtered sequence depends on the previous one. In addition to these, there are moving methods also based on the other average functions, in particular, the moving median model.

In data processing systems other processing methods are also used including spline interpolation in particular, in this case the recalculated subsequence values on each individual segment are characterized by a given polynomial order which coefficients have to be

calculated. However, the methods listed above are not suitable for ECG processing, since they cause significant distortions in the signal with sharp short peaks.

The smoothing method by Savitzky-Golay [15] filter becoming increasingly widespread, in this case instead of the linear approximation in the neighborhood of each point of the sequence an approximating  $n$ -th order polynomial is constructed by the least squares method in a certain length window. This sequence reconstruction back is performed by the smaller polynomial order calculation. The smoothing Savitzky-Golay filters (polynomial non recursive filters) are used for wide spectrum noisy signals smoothing (in the narrow sense). Such filters yield a much better result than ordinary non-recursive averaging filters (with ability to significant proportion of high-frequency significant signal components removing) make minimal phase distortions which is a critical condition for signal processing by synphase method. However, this smoothing method provides a bit worse noise attenuation compared to commonly used non-recursive filters, which requires a bit more computing resources. Since such a filtration provides a polynomial approximation of the input sequence individual frames by the minimum of the mean square error criteria that's why in this sense it is optimal.

Thus, the Savitsky-Golay filter is the most optimal technique, which does not distort the significant signal form under the optimal choosing of polynomial order and of the smoothing window width.

For the smoothing process quality estimation, we use two criteria:

- the P-wave maximum deviation value (horizontal displacement) after ECS and 1/0,05 amplitude ratio white noise additive mixture smoothing using Savitsky-Golay filter;
- the mean square deviation between real and filtered ECS.

The results are summarized in two tables.

The first one (Table 1) illustrates the P-wave maximum deviation dependence on the frame length and the smoothing polynomial order.

**Table 1**

The P-wave maximum deviation dependence on the window length and the Savitsky-Golay filter smoothing polynomial order

Deviation, <i>ms</i>	Filter frame length <i>F</i>										
		13	15	17	19	21	23	25	27	29	31
Smoothing polynomial order <i>O</i>	3	8	7	7	7	6	5	5	5	3	2
	4	7	7	7	6	5	5	4	4	2	2
	5	7	7	6	5	5	4	4	2	2	2
	6	7	6	5	5	4	4	2	2	2	1
	7	6	5	5	4	3	2	2	2	2	1
	8	5	5	4	4	2	2	2	2	1	1
	9	5	4	4	2	2	2	2	2	1	1
	10	5	4	2	2	2	2	2	1	1	0
	11	3	2	2	2	2	1	1	1	1	0
	12	2	2	2	1	1	1	1	0	0	0

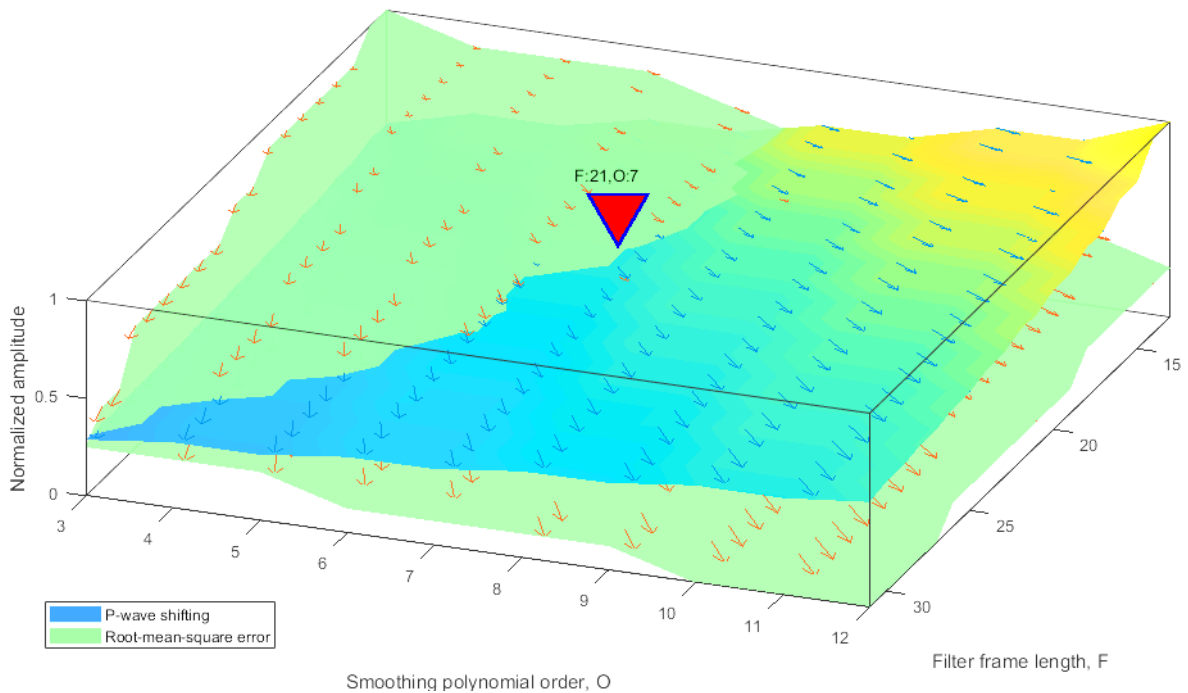
The second one (Table 2) illustrates the mean square deviation between real and filtered ECS dependence on the frame length and the smoothing polynomial order.

**Table 2**

Mean square deviation between real and filtered ECS dependence on the frame length and the Savitsky-Golay filter smoothing polynomial order

Deviation, <i>ms</i>	Filter frame length <i>F</i>										
		13	15	17	19	21	23	25	27	29	31
Smoothing polynomial order <i>O</i>	3	0,393	0,364	0,343	0,326	0,313	0,302	0,292	0,284	0,275	0,271
	4	0,501	0,464	0,434	0,407	0,385	0,367	0,352	0,340	0,329	0,319
	5	0,503	0,465	0,434	0,408	0,386	0,368	0,353	0,340	0,330	0,319
	6	0,592	0,547	0,513	0,484	0,459	0,436	0,416	0,398	0,381	0,368
	7	0,593	0,547	0,514	0,485	0,459	0,436	0,416	0,397	0,382	0,370
	8	0,684	0,626	0,580	0,549	0,521	0,497	0,476	0,456	0,439	0,419
	9	0,684	0,631	0,582	0,549	0,521	0,498	0,476	0,457	0,438	0,423
	10	0,790	0,707	0,654	0,610	0,576	0,548	0,526	0,506	0,487	0,471
	11	0,791	0,707	0,656	0,613	0,578	0,549	0,526	0,506	0,487	0,470
	12	0,943	0,804	0,726	0,674	0,636	0,602	0,573	0,548	0,530	0,511

For minimization problem solving the of fastest descent along intersection curve of parameter dependency planes gradient method is used.



**Figure 5.** The Savitsky-Golay filter optimal parameters choice optimization problem solving

The threshold method is used to find P-wave, since now there is no need to use different types of pattern recognition, pattern search, or transition to another area (for example, time to frequency domain transformation using Fourier transform, wavelet scaling coefficients).

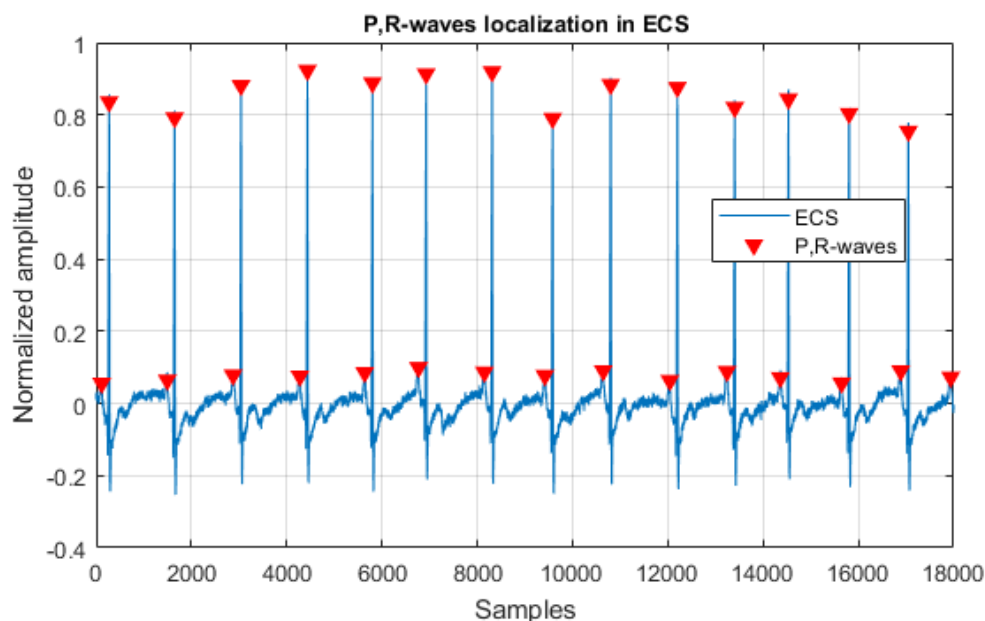


Figure 6. R-waves and P-waves localization in ECS

**Conclusions.** The applied preliminary processing algorithm makes it possible to reduce the noise negative influence during the FCS processing by synphase method and increase the results repeatability.

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## ОБҐРУНТУВАННЯ ВИБОРУ АЛГОРИТМУ ПОПЕРЕДНЬОГО ОПРАЦЮВАННЯ ФОНОКАРДІОСИГНАЛУ ЯК ПЕРІОДИЧНО КОРЕЛЬОВАНОГО ВИПАДКОВОГО ПРОЦЕСУ

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**Резюме.** Ціла низка екзогенних та ендогенних факторів чинить комплексний синергічний негативний вплив на стан серцево-судинної системи як основного адаптогена. Для його ранньої діагностики, зокрема у системах віддаленого моніторингу, запропоновано використати фонокардіосигнал (синхронно зареєстрований з електрокардіосигналом), який у термінах системно-сигнальної концепції є переносником відомостей про морфофункціональний стан серця. Як модель фонокардіосигналу використано періодично корельований випадковий процес (оскільки ця модель є адекватною до природи породження сигналу) та синфазний метод опрацювання, що дало змогу врахувати вплив нервової регуляції (синусового вузла як водія ритму). Синфазний метод вимагає забезпечення однорідності статистичного матеріалу та визначення періоду корельованості вхідної послідовності, який у випадку фонокардіосигналу може бути представлений як середня тривалість серцевого циклу. Визначення його за тривалістю R-R інтервалу не дає змоги забезпечити вибірку однієї окремої реалізації, тобто інтервалу між моментами прояву дії синусового вузла, що на електрокардіограмі виявляється P-зубцем. Тому запропоновано визначати одну реалізацію серцевого циклу як інтервал P-P. Наведено процедуру попереднього опрацювання зареєстрованого сигналу за алгоритмом: детрендинг сигналу (позбавлення від тренду, постійної складової сигналу), згладжування (позбавлення від високочастотних шумів з мінімальним спотворенням спектру та зміщенням локалізації P-зубців), знаходження періоду повторюваності за P-зубцями. Така модель фонокардіосигналу дає можливість удосконалення існуючих систем віддаленого кардіомоніторингу для виявлення змін у роботі серця на ранніх стадіях розвитку патологічного процесу шляхом упровадження нового класу інформативно-інваріантних ознак – спектральних компонент, отриманих у результаті опрацювання сигналу синфазним методом.

**Ключові слова:** біосигнал, кардіосигнал, фонокардіосигнал, математична модель, імітаційна модель, верифікація, алгоритми виявлення патології серця, MATLAB.

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