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MATHEMATICAL MODEL OF RHYTHMOCARDIOSIGNAL IN VECTOR VIEW OF STATIONARY AND STATIONARY-RELATED CASE SEQUENCES

Abstract. The paper deals with the substantiation of the mathematical model of rhythmocardiogram with high resolution in the form of a vector of stationary and stationary related random processes. The structure of probabilistic characteristics of this model for analysis of cardiac rhythm in modern cardiodiagnostic systems is investigated. Analysis of the heart rhythm makes it possible to evaluate not only the state of the cardiovascular system, but also the state of the adaptive capacity of the whole human body. Most modern systems of automated heart rate analysis are based on statistical analysis by a rhythmocardiogram, which is an ordered set of durations of R-R intervals in a registered electrocardiogram. be able to explore its temporal dynamics. To take into account the temporal dynamics of the rhythmocardiogram with high resolution, it is necessary to use a mathematical apparatus of the theory of random sequences, namely, to consider it as a vector of discrete random sequences. The purpose of this work is to solve the scientific and practical task of creating a mathematical model of rhythmocardiogram with high resolution in the form of a vector of stationary and stationary related random processes. The object of the study is information technology for the diagnosis and assessment of the status of the rhythmocardiogram to analyze the heart rhythm in modern cardiac diagnostics systems. The mathematical model of rhythmocardiogram with high resolution in the form of a vector of stationary and stationary related random sequences is substantiated. The structure of probabilistic characteristics of this model for analysis of cardiac rhythm in modern cardiodiagnostic systems is investigated.

Keywords: vector of steady-state and stationary-related random sequences; electrocardiogram; rhythm; cardiac rhythm.

Introduction

Analysis of the heart rhythm makes it possible to evaluate not only the state of the cardiovascular system, but also the state of the adaptive capacity of the whole human body. Most modern systems for automated cardiac rhythm analysis are based on statistical analysis by rhythmocardiogram, which is an ordered set of durations of R-R intervals in a registered electrocardiogram [1-8]. However, this approach is uninformative, since the R-R intervals reflect only the change in the duration of the cardiac cycles and not the totality of the time intervals between single-phase values of the electrocardio signal for all its phases.

Among the many varieties of environmental impacts, dust pollution from atmospheric air, which is formed as a result of receipt from sources of emissions at industrial enterprises (primary) and by physical and chemical processes in places of storage of pulverized wastes of production (secondary), among which special finely dispersed (<100 μm) saw dust is the place of disposal

Actuality of theme

In [9, 10], a new approach to its analysis of cardiac rhythm was developed on the basis of high resolution rhythmocardiogram. As noted in these papers, the classical rhythmocardiogram is embedded in a high-resolution rhythmocardiogram, which is the basis for increasing the level of informativeness of the heart rhythm analysis in modern computer systems of functional diagnostics of the human heart state with the increased rhythmocardiogram

In [9, 10] it is justified to use a vector of random variables as a mathematical model of rhythmocardiogram with high resolution. However, this model is a relatively poor mathematical model of rhythmocardiogram with high resolution, since it does not allow to study its temporal dynamics. To take into account the temporal dynamics of the rhythmocardiogram with high resolution, it is necessary to use a mathematical apparatus of the theory of random sequences, namely, to consider it as a vector of discrete random sequences.

Purpose and tasks of the work. The purpose of this work is to solve the scientific and practical task of creating a mathematical model of rhythmocardiogram with high resolution in the form of a vector of stationary and stationary related random processes. The object of the study is information technology for the diagnosis and assessment of the status of the rhythmocardiogram to analyze the heart rhythm in modern cardiac diagnostics systems.presenting main material.

Main part

One of the simplest stochastic models that takes into account the dynamics of high resolution rhymocardial is the vector xed and stationary random sequences. In this vector, the index indicates the cycle number of the electrocardio signal, and the index indicates the reference number of the electrocardio signal within its cycle. The number of counts per cycle of the electrocardio signal determines the resolution of the rhythm cardio signal and sets the number of phases in the cycle of the electrocardio signal that can be separated by methods of segmentation and detection in solving the problem of automatic formation of the rhythm cardio signal from the electrocardio signal.

Let us now proceed to justify the probabilistic characteristics of a random sequence vector $\Xi_L(\omega', m)$. One of the simplest stochastic models that takes into account the dynamics of high resolution rhymocardial is the vector $\Xi_L(\omega', m) = \left\{ T_l(\omega', m), \omega' \in \mathbf{\Omega}', l = \overline{1, L}, m \in \mathbf{Z} \right\}$ fixed and stationary random sequences. First of all, we note that the vector $\Xi_L(\omega', m)$ of stationary and stationary coupled random sequences, in the particular case if its constituents are stationary sequences with independent values, that is, white noises given on the set of integers, is a known rhythmocardiogram signal model. in the form of a random variable vector developed in [9, 10]. However, in practice, the hypothesis of the independence or non-correlation of the rhythm cardiogram counts is not true, requiring a stochastic dependence between the rhytocardiogram counts with higher resolution, and hence the use of a more complex and general mathematical model $\Xi_L(\omega', m)$ in the form of a stationary vector.

The defining property of a vector $\Xi_L(\omega', m)$ of stationary and stationary related random sequences is the invariance of its family of distribution functions to time shifts by an arbitrary integer $k \in \mathbf{Z}$. Namely, for any order distribution function

$$F_{p_{T_{l_1} \ldots T_{l_p}}}\left(x_1,\ldots,x_p, m_1,\ldots,m_p\right)$$

of the family p ($p \in \mathbf{N}$) of stationary distribution functions of stationary and stationary related random sequences, the following equality holds:

$$\begin{gathered} F_{p_{T_{l_1} \ldots T_{l_p}}}\left(x_1,\ldots,x_p, m_1,\ldots,m_p\right)= \\ = F_{p_{T_{l_1} \ldots T_{l_p}}}\left(x_1,\ldots,x_p, m_1+k,\ldots,m_p+k\right), \\ x_1,\ldots,x_p \in \mathbf{R}, m_1,\ldots,m_p \in \mathbf{Z}, \\ l_1,\ldots,l_p \in \left\{\overline{1,L}\right\}, k \in \mathbf{Z}. \end{gathered} \tag{1}$$

Distribution function

$$F_{p_{T_{l_1} \ldots T_{l_p}}}\left(x_1,\ldots,x_p, m_1,\ldots,m_p\right)$$

when $l_1 = l_2 = \ldots = l_p = l$ is distribution function $F_{p_{T_l}}\left(x_1,\ldots,x_p, m_1,\ldots,m_p\right)$, l is a distribution function $T_l(\omega', m)$, vector $\Xi_L(\omega', m)$ - auto-order distribution p of $T_l(\omega', m)$, describing the time distances between single-phase electrocardiogram readings for it l phases. In particular, if $p = 1$, then we will have one-dimensional $F_{1_{T_l}}\left(x, m\right)$ autofunction of stationary random sequence distribution $T_l(\omega', m)$.

In the case where equality $l_1 = l_2 = \ldots = l_p = l$ is not executed then the distribution function $F_{p_{T_{l_1} \ldots T_{l_p}}}\left(x_1,\ldots,x_p, m_1,\ldots,m_p\right)$ is a compatible distribution function for several (at least two) stationary components of a vector $\Xi_L(\omega', m)$, describing the time distances between single-phase counts of an electrocardio signal generally for its various phases. The vector distribution family of functions $\Xi_L(\omega', m)$ of stationary and stationary sequences most fully describes its probabilistic structure, but the methods of statistically estimating the distribution function $F_{p_{T_{l_1} \ldots T_{l_p}}}\left(x_1,\ldots,x_p, m_1,\ldots,m_p\right)$ are too cumbersome for their practical use in the computer diagnostic systems of the functional state of the cardiovascular system of the human body. Therefore, apart from the vector distribution functions. $\Xi_L(\omega', m)$ the use of momentary functions of order is effective $s = \sum_{j=1}^{p} s_j$, which, if any, are also invariant to time offsets (offsets by argument m).

Yes, if there is a mixed initial moment function $c_{s_{T_{l_1} \ldots T_{l_p}}}\left(m_1,\ldots,m_p\right)$ order $s = \sum_{j=1}^{p} s_j$ vector $\Xi_L(\omega', m)$ stationary and stationary random sequences, then it has equality:

$$\begin{gathered} c_{s_{T_{l_1} \ldots T_{l_p}}}\left(m_1,\ldots,m_p\right)= \\ = \mathbf{M}\left\{T_{l_1}^{s_1}\left(\omega', m_1\right)\cdot\ldots\cdot T_{l_p}^{s_p}\left(\omega', m_p\right)\right\}= \\ = c_{s_{T_{l_1} \ldots T_{l_p}}}\left(m_1+k,\ldots,m_p+k\right), \\ m_1,\ldots,m_p \in \mathbf{Z}, l_1,\ldots,l_p \in \left\{\overline{1,L}\right\}, k \in \mathbf{Z}. \end{gathered} \tag{2}$$

If there is a mixed central moment function b $r_{s_{T_{l_1} \ldots T_{l_p}}}\left(m_1,\ldots,m_p\right)$ order $s = \sum_{j=1}^{p} s_j$ of $\Xi_L(\omega', m)$ stationary and stationary random sequences, then it has equality:

$$\begin{gathered} r_{s_{T_{l_1} \ldots T_{l_p}}}\left(m_1,\ldots,m_p\right) = \mathbf{M}\left\{\left(T_{l_1}\left(\omega', m_1\right) - c_{1_{T_{l_1}}}\right)^{s_1} \times\right. \\ \left.\times\ldots\times\left(T_{l_p}\left(\omega', m_p\right) - c_{1_{T_{l_p}}}\right)^{s_p}\right\}= \\ = r_{s_{T_{l_1} \ldots T_{l_p}}}\left(m_1+k,\ldots,m_p+k\right), \\ m_1,\ldots,m_p \in \mathbf{Z}, l_1,\ldots,l_p \in \left\{\overline{1,L}\right\}, k \in \mathbf{Z}, \end{gathered} \tag{3}$$

where $\left\{c_{1_{T_{l_1}}},\ldots,c_{1_{T_{l_p}}}\right\}$ is the set of first-order initial moments (mathematical expectations) of stationary random sequences from the set $\left\{T_{l_1}(\omega', m),\ldots, T_{l_p}(\omega', m)\right\}$.

In practice, for analysis of high-resolution rhythm, it is reasonable to use mixed high-order moment functions, namely, mixed second-order initial moment functions - covariance functions and mixed second-order central moment functions - correlation functions. In this case, the initial second-order moment functions for the vector $\Xi_L(\omega', m)$ of stationary and stationary related random sequences are represented as a matrix of covariance functions:

$$\mathbf{C}_T = \begin{bmatrix} c_{2_{T_1 T_1}}\left(m_1, m_2\right) & \cdots & c_{2_{T_1 T_p}}\left(m_1, m_2\right) \\ c_{2_{T_2 T_1}}\left(m_1, m_2\right) & \cdots & c_{2_{T_2 T_p}}\left(m_1, m_2\right) \\ \vdots & \cdots & \vdots \\ c_{2_{T_p T_1}}\left(m_1, m_2\right) & \cdots & c_{2_{T_p T_p}}\left(m_1, m_2\right) \end{bmatrix} \tag{4}$$

which can be more compactly submitted as follows:

$$\mathbf{C}_T = \left[c_{2_{T_{l_1}T_{l_2}}}(m_1, m_2), l_1, l_2 = \overline{1, L} \right], \qquad (5)$$

where each of its elements is a covariance function $c_{s_{T_{l_1}T_{l_2}}}(m_1, m_2)$, which is given so:

$$c_{2_{T_{l_1}T_{l_2}}}(m_1, m_2) = \mathbf{M}\left\{ T_{l_1}(\omega', m_1) \cdot T_{l_2}(\omega', m_2) \right\}, \quad m_1, m_2 \in \mathbf{Z}, l_1, l_2 \in \left\{ \overline{1, L} \right\}. \qquad (6)$$

Since the components of a random sequence vector $\Xi_L(\omega', m)$ are stationary and stationary related sequences, their covariance functions are functions of only one integer argument u, which is equal. Therefore, the covariance matrix of this random vector can be represented as follows:

$$\mathbf{C}_T = \left[c_{2_{T_{l_1}T_{l_2}}}(u), l_1, l_2 = \overline{1, L} \right], \qquad (7)$$

where each of its elements is a covariance function $c_{2_{T_{l_1}T_{l_2}}}(u)$, which is equal to:

$$c_{2_{T_{l_1}T_{l_2}}}(u) = c_{2_{T_{l_1}T_{l_2}}}(m_1 - m_2), \quad u, m_1, m_2 \in \mathbf{Z}, l_1, l_2 \in \left\{ \overline{1, L} \right\}. \qquad (8)$$

Provided that $l_1 = l_2 = l$, the covariance function $c_{s_{T_l T_l}}(u)$ is an autocovariance function l stationary components $T_l(\omega', m)$ vector $\Xi_L(\omega', m)$, which describes the time distances between single-phase electrocardiogram readings for it l. If $l_1 \neq l_2$, then the covariance function $c_{2_{T_{l_1}T_{l_2}}}(u)$ function for two stationary components of a vector $\Xi_L(\omega', m)$, describing the time distances between single-phase electrocardiogram readings for l_1 and l_2 its phases. Mixed central second-order moment functions for a vector $\Xi_L(\omega', m)$ stationary and stationary related random sequences are presented as a matrix of correlation functions:

$$\mathbf{R}_T = \begin{bmatrix} r_{2_{T_1T_1}}(m_1, m_2) & \cdots & r_{2_{T_1T_p}}(m_1, m_2) \\ r_{2_{T_2T_1}}(m_1, m_2) & \cdots & r_{2_{T_2T_p}}(m_1, m_2) \\ \vdots & \cdots & \vdots \\ r_{2_{T_pT_1}}(m_1, m_2) & \cdots & r_{2_{T_pT_p}}(m_1, m_2) \end{bmatrix}, \qquad (9)$$

which can be presented more compactly so:

$$\mathbf{R}_T = \left[r_{2_{T_{l_1}T_{l_2}}}(m_1, m_2), l_1, l_2 = \overline{1, L} \right], \qquad (10)$$

where each of its elements is a correlation function $r_{s_{T_{l_1}T_{l_2}}}(m_1, m_2)$, which is given so:

$$c_{2_{T_{l_1}T_{l_2}}}(m_1, m_2) = \mathbf{M}\left\{ \left(T_{l_1}(\omega', m_1) - c_{1_{T_{l_1}}} \right) \cdot \left(T_{l_2}(\omega', m_2) - c_{1_{T_{l_2}}} \right) \right\}, \quad m_1, m_2 \in \mathbf{Z}, l_1, l_2 \in \left\{ \overline{1, L} \right\}. \qquad (11)$$

Because the components of the vector $\Xi_L(\omega', m)$ random sequences are stationary and stationary sequences, their correlation functions are functions of only one integer argument u, which is equal to $u = m_1 - m_2$. Therefore, the correlation matrix of this random vector can be represented as follows:

$$\mathbf{R}_T = \left[r_{2_{T_{l_1}T_{l_2}}}(u), l_1, l_2 = \overline{1, L} \right], \qquad (12)$$

where each of its elements is a correlation function $r_{2_{T_{l_1}T_{l_2}}}(u)$, which is equal to:

$$r_{2_{T_{l_1}T_{l_2}}}(u) = r_{2_{T_{l_1}T_{l_2}}}(m_1 - m_2), \quad u, m_1, m_2 \in \mathbf{Z}, l_1, l_2 \in \left\{ \overline{1, L} \right\}. \qquad (13)$$

Provided that $l_1 = l_2 = l$, correlation function $r_{2_{T_l T_l}}(u)$ is an autocorrelation function l stationary components $T_l(\omega', m)$ vector $\Xi_L(\omega', m)$, which describes the time distances between single-phase electrocardiogram readings for him l- phases. If $l_1 \neq l_2$, then the correlation function $r_{2_{T_{l_1}T_{l_2}}}(u)$ is a reciprocal correlation function for two stationary components of a vector $\Xi_L(\omega', m)$, describing the time distances between single-phase electrocardiogram readings for l_1 and l_2 phases.

Fig. 1-4 shows the results of statistical processing of the rhythm cardio signal with high informativeness, by statistical evaluation of its corresponding statistical characteristics.

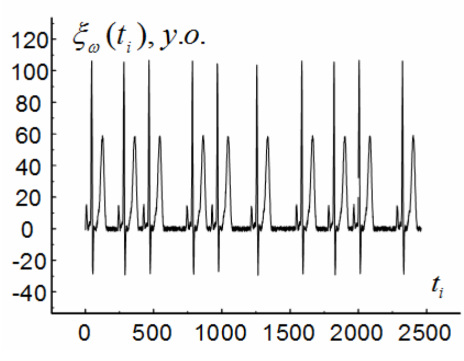
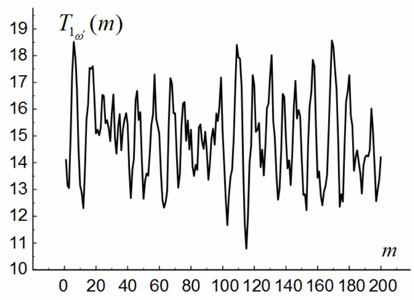


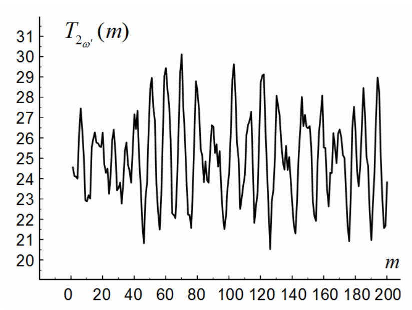
Fig. 1. Several cycles of the investigated electrocardio signal

Conclusions

The mathematical model of rhythmocardiogram with high resolution in the form of a vector of stationary and stationary related random sequences is substantiated. The structure of probabilistic characteristics of this model for analysis of cardiac rhythm in modern cardiodiagnostic systems is investigated.

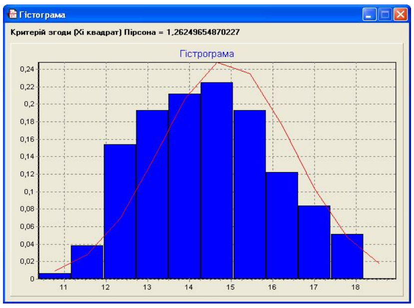


a

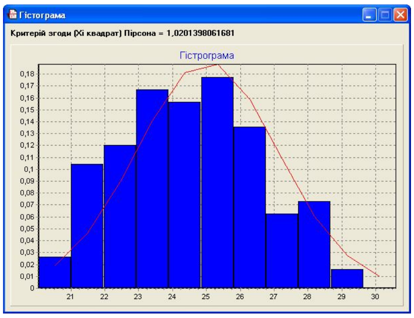


b

Fig. 2. Schedule of sales $T_{1_{\omega'}}(m)$, $T_{2_{\omega'}}(m)$ component of the vector rhythmocardiogram of the first component $T_1(\omega', m)$ and the second component $T_2(\omega', m)$, describing duration respectively: a – P, electrocardio signal intervals; b – R, electrocardio signal intervals

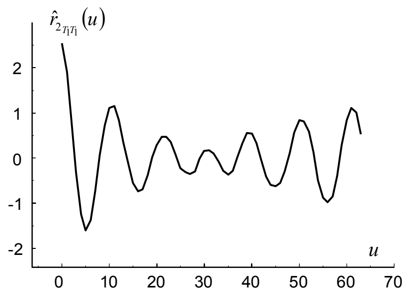


a

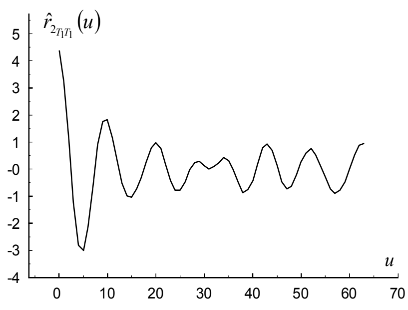


b

Fig. 3. Implementation histograms $T_{1_{\omega'}}(m)$, $T_{2_{\omega'}}(m)$ component of the vector rhythmocardiogram of the first component $T_1(\omega', m)$ and the second component $T_2(\omega', m)$, describing duration respectively: a – P, electrocardio signal intervals; b – R, electrocardio signal intervals



a



b

Fig. 4. Schedule of sales $\hat{r}_{2_{T_1T_1}}(u)$ statistical estimates of autocorrelation functions $r_{2_{T_1T_1}}(u)$ ($l_1 = l_2 = 1$) the first components $T_1(\omega', m)$ and the second component $T_2(\omega', m)$, describing duration respectively: a – P, describing duration respectively; b – R, electrocardio signal intervals

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Математична модель ритмокардіосигналу у вигляді вектора стаціонарних та стаціонарно пов’язаних випадкових послідовностей

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Анотація. Робота присвячена обґрунтуванню математичної моделі ритмокардіосигналу із підвищеною роздільною здатністю у вигляді вектора стаціонарних та стаціонарно пов’язаних випадкових процесів. Досліджено структуру ймовірнісних характеристик цієї моделі для аналізу серцевого ритму у сучасних системах кардіодіагностики. Аналіз ритму серця дає змогу оцінювати не лише стан серцево-судинної системи, але і стан адаптивних можливостей цілого організму людини. Більшість сучасних систем автоматизованого аналізу серцевого ритму ґрунтуються на статистичному аналізу за ритмокардіограмою, яка є упорядкованою сукупністю тривалостей R-R-інтервалів в зареєстрованому електрокардіосигналі, що дає змогу досліджувати її часову динаміку. Для врахування часової динаміки ритмокардіосигналу із підвищеною роздільною здатністю необхідно використовувати математичний апарат теорії випадкових послідовностей, а саме, розглядати його як вектор дискретних випадкових послідовностей. **Метою роботи** є розв’язання науково-практичного завдання створення математичної моделі ритмокардіосигналу **з** підвищеною роздільною здатністю у вигляді вектора стаціонарних та стаціонарно пов’язаних випадкових процесів. **Об’єкт дослідження** є інформаційні технологій для діагностики і оцінки стану ритмокардіосигналу для аналізу серцевого ритму у сучасних системах кардіодіагностики. У роботі обґрунтовано математичну модель ритмокардіосигналу із підвищеною роздільною здатністю у вигляді вектора стаціонарних та стаціонарно пов’язаних випадкових послідовностей. Досліджено структуру ймовірнісних характеристик цієї моделі для аналізу серцевого ритму у сучасних системах кардіодіагностики.

Ключові слова: вектор стаціонарних та стаціонарно-пов’язаних випадкових послідовностей; електрокардіосигнал; ритмокардіосигнал; серцевий ритм.

Математическая модель ритмокардиосигнала в виде вектора стационарных и стационарно связанных случайных последовательностей

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Аннотация. Работа посвящена обоснованию математической модели ритмокардиосигнала с повышенной разрешающей способностью в виде вектора стационарных и стационарно связанных случайных процессов. Исследована структура вероятностных характеристик этой модели для анализа сердечного ритма в современных системах кардиодиагностики. Анализ ритма сердца позволяет оценивать не только состояние сердечно-сосудистой системы, но и состояние адаптивных возможностей целого организма. Большинство современных систем автоматизированного анализа сердечного ритма основываются на статистическом анализа по ритмокардиограмме, которая является упорядоченной совокупности длительностей R-R-интервалов в зарегистрированном электрокардиосигналов, что дает возможность исследовать ее временную динамику. Для учета временной динамики ритмокардиосигнала с повышенной разрешающей способностью необходимо использовать математический аппарат теории случайных последовательностей, а именно, рассматривать его как вектор дискретных случайных последовательностей. **Целью работы** является решение научно-практической задачи создания математической модели ритмокардиосигнала с повышенным разрешением в виде вектора стационарных и стационарно связанных случайных процессов. **Объектом исследования** являются информационные технологии для диагностики и оценки состояния ритмокардиосигнала для анализа сердечного ритма в современных системах кардиодиагностики. В работе обоснована математическая модель ритмокардиосигнала с повышенной разрешающей способностью в виде вектора стационарных и стационарно связанных случайных последовательностей. Исследована структура вероятностных характеристик этой модели для анализа сердечного ритма в современных системах кардиодиагностики.

Ключевые слова: вектор стационарных и стационарно-связанных случайных последовательностей; электрокардиосигнал; ритмокардиосигнал; сердечный ритм.