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THE COMPARATIVE ANALYSIS OF MATHEMATICAL MODELS OF CYCLIC SIGNALS STRUCTURE AND PROCESSES

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***Summary**. The article deals with the comprehensive research of the possibilities, perspectives and efficiency of the application of the popular mathematical models of cyclic signals and processes on the basis of mathematical support of information systems' analysis. The forecasting and imitation, the comparative analysis of a wide range of mathematical objects, that is used or can be used as the models of signals and processes of cyclic structure. The comprehensive research will help researchers to select and adapt reasonably (adequately studied signal structure and objectives of the study) mathematical model of the existing totality that significantly improve performance (simplify and speed up) the development of software for designed information system.*

***Key words:** cyclic signals, cyclic processes, mathematical models, comparative analysis*

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Problem setting. The elaboration of modern automated information systems for processing and imitation of cyclic signals of different origin is a basis for the improvement of efficiency, accuracy, authenticity and informative content of analysis, identification, diagnostics and forecasting of system conditions. The typical examples of such systems are computer-based cardio-diagnostic systems, information systems for analysis and forecasting of cyclic economic processes, individual's authentication due to his/her biometric dynamic data, analysis and forecasting of electricity, water, gas and oil consumption, software and hardware devices to generate and imitate the cyclic processes.

The first and crucial stage at designing of informational systems for processing and imitation of cyclic signals is the creation of their mathematical models properly reflecting the important for the research sides of space-and time structure of cyclic signals. The mentioned above mathematical model promotes considerably the IT potential and efficiency, stipulates the structure of software and hardware of designed information system. The accuracy and authenticity of processing and imitation methods within the information system, the level of informative content and representation of diagnostic, verifying, identifying and forecasting features as well as the authenticity of of decisions depends greatly on the quality of mathematical model for cyclic signals (see Figure 1).

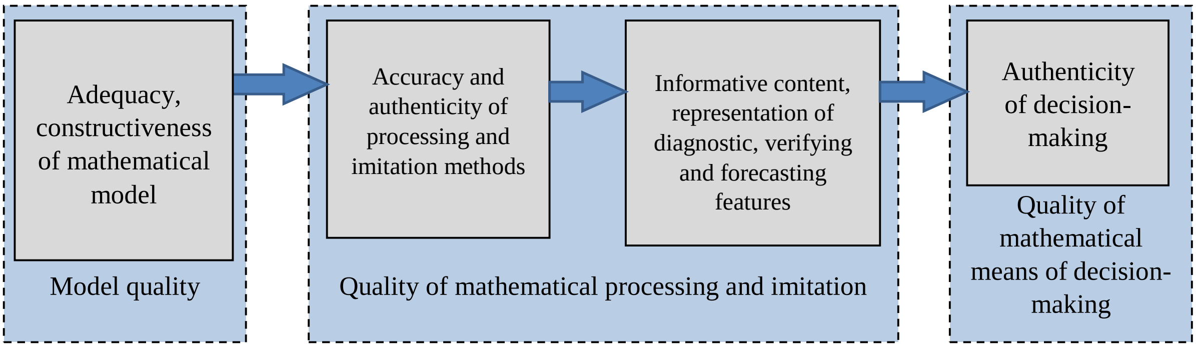

Figure 1. The reason and consequence relations regarding the quality of automated information system of processing and imitation of cyclic signals.

Analysis of the latest researches and issues. A lot of scientific issues have been devoted to mathematical models of cyclic phenomena and signals. As it was stated in the monograph [1] within the determining approach to mathematical modeling and processing of cyclic signals the remarkable results were obtained by such well-known scholars as Bezykovich, Boor, Ball, Winner, Gonorowski, Dirihle, Rytov, Stepanov, Fourier (cyclic signals structure modeling within periodic, almost periodic, quasi-harmonic functions, quasi-meander and spectral analysis methods). There are also Andronov, Bogoliubov, Krylov, Lapunov, Mandelstam, Poincare (modeling of mechanisms to form the cyclic signals by means of differential equities). Among the prominent scholars, dealing with mathematical modeling and analysis of cyclic processes within theory of probability, one has to mention Kramar, Kolmogorov, Slutskiy, Hinchin (spectral-correlative theory of immobile random processes), Garry, Guard, Gardener, Kallianpur, Woichyshyn, Gladyshev, Dragan, Korynkevych, Sikora, Stratovych, I.Yavorskyy, B. Yavorskyy (the theory of periodically correlated (cyclic immobile correlated) and almost periodically correlated (almost cyclic immobile correlated) random processes), Bohme, Hansen, Gaisels, Dorogovtsev, Kohl, Nematollahi, Pryimak, Sargent, Soltani, Tse (theory of Mark periodic random processes and chains), Dragan, Kasilnikov, Lupenko, Marchenko, Pryimak, Scherbak (theory of linear periodic random processes and fields, processes with independent periodic increments and periodic white noises), Lupenko (theory of cyclic random processes and vectors).

Research goals. Due to considerable number of existing mathematical models of cyclic signals' structure and their great variety there is no necessity to build from the «zero» level the new mathematical model and cyclic signals' processing methods during creation of certain information system for processing and imitation of cyclic signals. It is better to select and adapt (due to the structure of studied signals and research goals) the mathematical model out of their available multiplicity in order to improve the efficiency (simplify and accelerate) of mathematical supply of designed information system. The correct and substantiated selection of mathematical model assumes the availability of compact and comfortable form of data about determining properties of existing mathematical models, their analysis methods and application efficiency for the solution of relevant tasks. That is why it is necessary to run the analytical survey and comparative analysis of the existing mathematical models of cyclic signals in order to characterize them from the viewpoint of their determinative properties, assessment of analysis methods, practical application, possibilities of efficient solutions for typical classes of tasks (imitation analysis, identification and forecasting) that are available during the process computer-aided design of information systems for processing and imitation of cyclic signals.

This research project contains the comparative analysis of wide class of mathematical objects that are used as models of cyclic signals and processes with the purpose to investigate the potential, prospects and efficiency of application of mathematical models for cyclic processes as a basement of mathematical background of information systems in terms of their analysis, forecasting and imitation.

Task setting. To reach the goal it is necessary to solve the following tasks:

1) identify the class of studied mathematical models for cyclic signals and define the list of properties for investigation and comparison of mathematical models for cyclic signals;

2) carry out the comparative analysis of mathematical models for cyclic signals; 3) to sum up the results of comparative analysis in the form of comparative table.

Research results.

The definition of mathematical models for cyclic signals and their properties to study and compare the mathematical models. The scientific issues conditionally state the two approaches to elaboration of mathematical models for cyclic signals as constructive and axiomatic ones. These two approaches are relevant to two large classes of mathematical models for signals, particularly to constructive models or system models that form (generate, originate) the studied signals, and axiomatic mathematical models for signals or models of data structure (spatial-temporal structure of signals). The constructive approach emphasizes on the construction and investigation of the model for not cyclic signal itself but the algorithm of its origin (generation, formation), particularly by means of recording of differential or integral equation describing the fluctuation system originating the studied signal. The constructive approach also contains the Fourier series and integral theory, module fluctuations models where complex fluctuations consist of simple (harmonic, periodic) ones, models of auto-regression of sliding with periodic or almost periodic change of their rates. Axiomatic approach focuses more on modeling of the rules of cyclic signal's spatial-temporal structure than on its origin, i.e. the axiomatic mathematical models for cyclic signals describe directly the spatial-temporal evolution of studied signals.

The research project concentrates mainly on comparative analysis of mathematical models for cyclic signals and processes within the axiomatic approach as the selection or creation of the most constructive models assumes the knowledge about peculiarities and properties of spatial-temporal structure of studied signals that is intrinsic for the axiomatic models.

The analytical research and comparison of the models will be mainly carried out due to their capability to reflect the remarkable properties of cyclic signals and the possibility, efficiency of their application with the purpose to solve the applied problems during designing of mathematical supply for automated information systems of processing and imitation (generation) of cyclic signals.

Comparative analysis of models for cyclic signals.

Determined mathematical models for cyclic signals and phenomena. The determined models have been used for ages to investigate many cyclic processes and phenomena within repeated actions in their spatial-temporal structure. The historically first and simplest mathematical model of fluctuations has been a harmonic function, which can be presented as sinusoid or con-sinusoid function. The harmonic function describes the elementary oscillator being a derivative of such real fluctuation systems as physical pendulum and electrical fluctuation contour. In information systems of analysis and forecasting of cyclic signals on the basis of their models as harmonic functions there is a minor multiplicity of analysis possibilities for such signals because the structure of the most real signals is much more complicated than the structure of harmonic function. Those are the harmonic functions that are predominantly used as constituents of more complex mathematical models like multi-harmonic functions or are the first approximation to the studied cyclic signals.

General manifestation of harmonic fluctuation is periodic fluctuation, which can be mathematically described by means of periodic function. The periodic functions are well studied and known mathematical models of cyclic signals and fluctuations, and their harmonic analysis have been for a long time a classic method in many applied researches. Despite the wide usage of periodic functions as basic, etalon models of fluctuations, they are rather simplified, idealized models of real phenomena. They can also describe the cyclic signals with sufficiently regular, well ordered time structure, which obeys the similar tempo of unfolding in time of signal cycles and where random factors are practically absent or when neglecting of contingency does not result in essential distortions and simplifies the accomplishment of given research tasks. The most of real fluctuation phenomena and signals do not satisfy these conditions that considerably limits the usage of determined periodic functions as mathematical models of cyclic signals for their analysis in information systems.

The diversification and generalization of periodic functions theory, methods of their analysis and synthesis were made by means of introduction of almost periodic function. There are some definitions of almost periodic function, particularly the definition of almost periodic function in terms of its time and spectral properties. Almost periodic functions facilitate taking into account the irregular character of real cyclic signals' time structure that is not inherent to periodic determined functions. The class of almost periodic functions is very wide and has quite general properties that do not reflect entirely the fluctuation, cyclic structure of real signals and phenomena. Amongst almost periodic functions, there are functions whose structure does not contain at all any specific peculiarities of fluctuation process. Besides, the almost periodic function does not take into consideration the stochastic (random) character of real signals as it belongs to determined mathematical objects. Due to almost periodic function, one can hardly take into account the variability of fluctuation process rhythm. That is why almost periodic and quasi-periodic functions are not popular while modeling and processing of cyclic signals in information systems.

Stochastic mathematical models of cyclic signals and phenomena. The modern research of cyclic, fluctuation phenomena and signals use the theories of probability, random processes and mathematical statistics, i.e. it is carried out within probabilistic (stochastic) apparatus. The simplest mathematical model of cyclic signals, which lies in the basis of the most methods of its processing in automated systems of diagnostics, in particular cardio diagnostics, ophthalmalgia diagnostics and biometric authentication of an individual, is a vector of random values that describes the multiplicity of check points (sections, parameters) for the cycles of cyclic signal. The random values vector is relatively "poor" in terms of informative content for mathematical model of cyclic signals that limits full-scale research of their structure.

Another approach to modeling of cyclic signals within stochastic paradigm is application of mathematical models in the form of such random functions as random processes and fields. It facilitates more complete reflecting of cyclic signals peculiarities in comparison with their models in the form of random values vector as the latter characterize the signal only with certain finite multiplicity of in advance selected cycle check elements. Amongst the simplest mathematical models, being used for description of cyclic signals as random processes, there is an immobile random process. It means the random processes, where initial momentum function of the first range and correlation function, are invariants in terms of their arguments translations (immobile random process in wide meaning) or multidimensional functions of distribution do not depend on time shift in terms of an aggregate of arguments (immobile random process in narrow meaning).

Despite the remarkable success of the theory of immobile random processes concerning the description and modeling of cyclic phenomena, the immobile model takes into account the cyclic character only in terms of availability of harmonic components in the structure of random process. This gives the possibility to study its spectral contents but probabilistic characteristics of the process itself do not contain any cyclic character because the harmonics of immobile process spectrum are non-correlated.

The next stage in development of stochastic models of fluctuations and cyclic signals was the creation of the theory of stochastic periodic random processes (in English-language issues it is called a theory of cyclic immobile random processes), i.e. such processes where certain probabilistic features are the periodic time functions. The known simplest probabilistic models of cyclic signals based on stochastic periodicity concept are additive, multiple and additive-multiple ones that are mainly used during preliminary processing of signals, particularly in problems of identification and filtration of the signals from obstacles [2, 3]. These models are simplified and do not embrace the entire structural diversity of real cyclic signals that makes it impossible to improve their description up to the level necessary for the requirements of modern science and technics.

The periodically correlated random processes (PCRP) have been fruitfully and for a long time used in modeling of cyclic signals and fluctuations. PCRP is a random process whose mathematical expectation is a periodic function with certain period and the correlation function is periodic with the same period due to an aggregate of its arguments [4 – 12]. In some English-language issues the PCRP is called cyclic immobile correlated random processes [13, 14]. PRCP definition was firstly made by Koronkevich [4] where the mentioned processes are considered to be the solutions for differential equations with periodic coefficients that are the mathematical models of fluctuation systems under influence of random perturbing forces. To analyze the signals based on their mathematical models in the form of PCRP they elaborated co-phased, component and filtering methods of processing. The model of cyclic signal in the form of PRCP takes into account only its two momentum functions: mathematical expectation and correlation function. The upper momentum and distribution functions cannot be represented on its basis. During spotting of measurement results deviations and statistic processing of signals, one should be aware of upper than second range momentums even within correlation theory. Only random process with normal distribution describes PCRP completely.

The more strict description of periodic character of cyclic signal can be made with periodic random process with periodic in terms of time arguments aggregate. All its finite measured distribution functions are a natural summarizing of additive, multiplicative, and additive-multiplicative models as well as periodically correlated random process. Stochastic periodic processes are widely used as mathematical models of modulated radio signals, cyclic cardio signals, cyclic economic phenomena, public services' requests. Spectral and time assessments of probabilistic characteristics for stochastic periodic processes are obtained by means of φ-series method being equivalent to co-phased method of PRCP stochastic analysis.

A number of known random processes with some periodic probabilistic characteristics like processes with independent periodic surpluses [15], processes with independent periodic values (periodic white noises) [15], Markov periodic random processes and chains [16 – 20], linear periodic random processes and coherences [21 – 24] are also used for mathematical modeling of cyclic processes. The processes with independent (non-correlated) surpluses describe properly the relatively simple streams of requests in mass service systems functioning in fluctuation mode (e.g.: energy, gas and water supply systems). They also play an important role as originating ones (they are basic probabilistic mathematical models) that are fundamental for important random processes classes with periodic probabilistic characteristics, i.e. they are essential for definitions of periodic white noise and linear periodic random processes. However, as result of relative simplicity of probabilistic structure of these random processes, their application as mathematical models of cyclic signals is limited.

The periodic white noise, which is determined to be a summarized derivative of the process with independent periodic surpluses, is mainly used as a mathematical model of various obstacles in radio-physics, radio-technics, and acoustics. The main information features describing noises and obstacles is their mathematical expectation, dispersion, and distribution function based on their model in the form or periodic white noise.

Markov periodic random processes and chains are mainly used for mathematical modeling of cyclic economic phenomena and energy network loadings. The data features in information systems of cyclic signals analysis on the basis of their model in the form of Markov periodic process can be presented as its periodic probabilistic characteristics: mathematical expectation, dispersion, one-dimensional distribution function and conditional distribution function. In case Markov periodic chains are used, the periodic matrixes of probabilities for transition between chain conditions reflecting the conditions of modeled discrete system can be interpreted as such data features. The positive output of Markov periodic models is the fact that all information about cyclic process is concentrated in two-dimensional distribution function that indicates the high data compactness of this mathematical model. The main disadvantage of Markov models is limited cyclic phenomena class where Markov property is located.

The linear periodic random processes (LPRP) and coherences, which can be studied within distribution functions, are widespread among theoretical and applied researches, particularly modeling of radio technical signals, technical diagnostics, hydro-acoustics, geophysics, and medical diagnostics. The nucleus (or its parameters) and probabilistic characteristics of originating process are used in information systems of cyclic signals analysis on the basis of their models in the form of LPRP as diagnostic features. The main advantage of linear periodic random process is its constructiveness as it facilitates using of LPRP for computer imitation of cyclic signals. In to the bargain, having used LPRP one could describe and analyze the cyclic signals within multidimensional distribution functions and characterizing functions. LPRP disadvantage is its complex and ineloquent procedure of nucleus and originating process parameters definition in terms of given LPRP probabilistic characteristics.

The generalization of periodic (periodically correlated) random process is almost periodic (periodically correlated) random process i.e. such random process where distribution functions (mathematical expectation and correlation function) are almost periodic with almost the same periods (or with the same Fourier indicators). The random processes being periodically, multi-periodically or almost periodically distributed are called cyclically distributed [8]. The class of almost periodic random processes is a very wide class of random processes as it is based on the almost periodicity notion, which as it was shown above is much too broad generalization of periodicity notion and is not a complete equivalent to cyclicity notion. The comprehensive research of such random processes have been made by Koronkevich, Gladyshev, Stratonovych, Rytov, Gardner, Hurd, Dragan and others.

In general, the periodicity (stochastic or determined) notion does not totally cover the cyclicity contents but is only its constituent as the property of periodicity postulates the values' recurrence or probabilistic characteristics of cyclic signal via the strict number, which is called a period, and such strict recurrence is absent inside the structure of the most cyclic signals. The determined periodic and stochastic periodic functional dependencies describe adequately only the certain part of cyclic structure of studied signals like cyclic signals with stable rhythm. Let us have an insight under this context into a number of approaches to elaboration of mathematical models and methods to process the cyclic signals with changing rhythm that take into account various deviations from periodic model both in determined and stochastic problems of modeling.

Methods of periodic signals modulation is an approach to modeling and formation of cyclic signals. In particular, the information message in radio technical transition systems is included in the parameters of high frequency periodic signal (bearing signal). The latter is mainly represented with harmonic and impulse high frequency signals. If the bearing signal is harmonic one, they use amplitude angle (frequency, phase) modulations and combinations of these modulations like amplitude-frequency one. Quasi-harmonic function, where the rhythm variability is added to momentum angle frequency [25] and momentum period [26] is a mathematical model of resulting modulated signal. In case the bearing signal is impulse periodic one (meander), they use amplitude-impulse, frequency-impulse, phase-impulse, band-impulse modulation types as well as their some combination. In this case, the rhythm variability affects the rate [27, 28] and changeable period [29]. Quasi-harmonic function like almost periodic function is a broad generalization of periodic functional dependency but as result of such width, it is not always useful for description of cyclic signals structure as it also covers non-cyclic rules of spatial-temporal signals structure.

The modulation of periodic bearer does not necessarily result in formation of cyclic signal; the outgoing signal can be non-cyclic. The cyclic signal appears only in case of re-modulation that ends up with «phase skip» in bearing signal. Moreover, the cyclicity of amplitude-modulated signal will be represented in other terms than cyclicity with angle modulation. The most real cyclic signals of natural, particularly biological origin can be hardly ever described on the basis of modulated periodic functions as they are extremely complicated and diversified in time; so such models became useful at designing of communication systems as the models for message bearers.

The problem of difficulties with variable rhythm cyclic signals modeling based on periodic random process was partially solved in [23], which deals with computer-based research of wide classes of cardio signals. These issues indicate that stochastic periodic methods of cardio signals processing have a negative effect of «fuzzy» of statistic data for cardio signals because of averaging of non-monophasic (heterogeneous) countdowns of a cardio signal because of the non-variability at the interval during their selection from the signal. Such contemporary interval of selection and averaging of countdowns is a period of its model in the form of periodic random process.

The notion of zonetime structure of cyclic signals was introduced in [23]. It enabled creation of mathematical model and methods of cyclic cardio signals processing including the instability, variability of time intervals between monophasic values in various cycles of cardio signals and «fuzzy» effect elimination at statistical characteristics of cardio signals. The incomplete elimination of unwanted effect was caused with law rate of detailing at zonetime structure of cyclic signals because the zone was interpreted as cardio signal section containing the whole multiplicity of its values. Therefore, the variability of time intervals was strictly spotted only for the momentums beginning and ending of the registered cardio signals' zones but not for the whole range of its monophasic values.

An attempt to count on the shift in time intervals between all monophasic values of cyclic signal was made in [30] where the notions «conditionally periodic with variables periodic random process» and «variable period» were introduced with the purpose to depict cyclic signal rhythm variability. However, the mentioned issue does not reveal many important questions like necessary and sufficient data concerning the cyclicity of conditions for so-called variable period. It bereft the researches the possibility to determine precisely the class of functions because the determinative feature in the form of its cyclicity had not been derived.

The determined, stochastic, fuzzy and interval mathematical models, imitation, discretion, statistical and spectral methods for analysis of cyclic signals were studied in [1], which is devoted to new theoretical fundamentals of mathematical modeling, computer simulation and processing of cyclic signals within the unified methodological approach. The special attention was paid to mathematical modeling and processing cyclic signals with variable rhythm. Owing to definition of abstract cyclic functional correlation as summarized mathematical model of cyclic signals by means of identifying of required and sufficient rhythm conditions, there were developed the mathematical fundamentals for the theory of modeling and processing of cyclic signals in information systems. That enabled the creation of their new mathematical models like digital, vector, matrix, cyclic determined functions, cyclic in terms of intervals multiplicity digital function, cyclic random process and vector of cyclic rhythmic random processes describing a wide range of possible attributes for cyclicity, considerable structural diversity of variability and rhythm convergence rules as well as possessing rhythm variability adaptation.

The cyclic random process is a generalization of stochastic periodic random process and is effisienly used for the modeling and analysis of cyclic cardio signals of diferetn physical nature (electric, magnetic, acoustic), cyclic economic phenomena and crack propagation [31-35]. They differentiate the class of cyclic random processes for discrete and continuous arguments, cyclic white noises, processes with independent cyclic surpluses, Markov cyclic random processes, linear cyclic random processes that sum up the existing stochastic model of cyclic signals in the form of relevant classes of stochastic periodic random processes.

For the modeling and compatible statistical analysis of correlated cyclic signals and processes evoked with the same fluctuations and with the same rhythmic structure, they use efficiently their mathematical model in the form of a vector with of cyclic rhythmically correlated random processes. The latter includes the vector of periodic random processes and facilitates an adequate description of variability coincidence of the studied rhythm for cyclic signals.

The cyclic sets of intervals comprising the digital functions and cyclic fuzzy functions take into consideration the fuzzy recurrence of cyclic signals within L. Zade theory of fuzzy multiplicities and interval methods of presented data. They can be successfully used in cyclic processes modeling under conditions of excessive irregularity of fluctuations and small number of its registered cycles when determined and stochastic approaches are inefficient because they produce low accuracy and authenticity of cyclic signals analysis under mentioned conditions. However, if one uses an expert’s evaluation like in the theory of fuzzy multiplicities or with interval methods of data representation, then acceptable enough analysis and forecasting results for such cyclic processes can be obtained. The methods of computer imitation were created for cyclic functional correlations (in particular, for digital and vector cyclic determined functions), relatively cyclic multiplicity of function intervals, random processes and vectors with cyclic probabilistic characteristics (in particular, cyclic white noises), processes with independent cyclic surpluses and Markov cyclic random processes. They also elaborated their computer-based imitation methods that increased the class of imitated cyclic signals up-graded their simulation methods by means of newly introduced precise software and hardware instruments due to available procedure of generating algorithm identification, simultaneous application of morphological characteristics and parameters of imitated signals rhythm. The summary of comparative analysis of mathematical models for cyclic signals is given in Table 1.

Table № 1.
Mathematical models of cyclic signals

			PROPERTIES OF CYCLIC SIGNALS							
			CYCLICITY OF SIGNALS	MULTIDIMENSIONAL CYCLICITY	OBSCURED VALUES OF SIGNALS	LOW ACCURACY OF SIGNALS	RANDOM CHARACTER OF SIGNALS	RHYTHM VARIABILITY	RHYTHM VARIATIONS DUE TO INADVERTENT LAW	RHYTHM CIINCIDENCE
POPULAR MATHEMATICAL MODELS OFCYCLIC SIGNALS	**DETERMINED**	HARMONIC FUNCTION	+	–	–	–	–	–	–	–
		PERIODIC FUNCTION	+	–	–	–	–	–	–	–
		QUASI-HARMONIC FUNCTION	+	–	–	–	–	+	+	–
		ALMOST PERIODIC FUNCTION	+/–	–	–	+	–	+/–	–	–
		QUASI-MEANDER (MODULATED MEANDER)	+	–	–	–	–	+	+	–
	STOCHASTIC	IMMOBILE RANDOM PROCESS	+/–	–	–	+	+	–	–	–
		STOCHASTIC PERIODIC PROCESS (PQRP, PCRP, LPRP ETC)	+	+	–	+	+	–	–	–
		PERIODIC RANDOM VECTOR	+	+	–	+	+	–	–	+
		ALMOST PERIODIC RANDOM PROCESS	+/–	+/–	–	+	+	+/–	–	–
		QUASI-HARMONIC RANDOM PROCESS	+/–	+/–	–	+	+	+/–	+/–	–
		VECTOR OF PERIODIC IN TIME VARIOUS PERIODS OF RANDOM PROCESSES	+	+	–	+	+	+	–	–
MODELS OF CYCLIC FUNCTIONAL CORRELATIONS		CYCLIC DIGITAL FUNCTION	+	–	–	–	–	+	+	–
		INTERVAL CYCLIC FUNCTION	+	–	–	+	–	+	+	–
		CYCLIC RANDOM PROCESS	+	+	–	+	+	+	+	–
		VECTOR OF CYCLIC RHYTHMICALLY LINKED RANDOM PROCESSES	+	+	–	+	+	+	+	+
		FUZZY CYCLIC FUNCTION	+	–	+	–	+	+	+	–

«+» – accounts on, «–» – does not account on, «+/–» – accounts on partially.

Summary.

1. The authors carried out the comparative analysis of mathematical models for signals and processes from the viewpoint of identification of their differential features, spatial-temporal properties of cyclic signals and possibilities to elaborate their computer-based processing methods.

2. As the result of accomplished comparative analysis, there were studied the potential, prospects and efficiency of popular mathematical models for cyclic signals and processes as a basement for mathematical support of computer-based analysis, diagnostics and forecasting systems.

3. The presented comprehensive analytical research can logically substantiate the elaboration of expert IT systems to sustain the mathematical modeling for computer-based processing of cyclic spatial-temporal signals.

References

1. Lupenko S.A. Teoretychni osnovy modeliuvannia ta opratsiuvannia tsyklichnykh syhnaliv v informatsiinykh systemakh. Naukova monohrafiia. Lviv: Vydavnytstvo “Mahnoliia 2006”, 2016. 344 p. [In Ukrainian].

2. Santopetro R.F. Proisxozhdenie i xarakteristiki osnovnogo signala, shuma i navodki v vysokochastotnoj e'lektrokardiogramme. TIIE'R. 1977. Vol. 65, no. 5. Pp. 137-145. [In Russian].

3. Malik M., Xia R., Odemuyiwa O. Influence of the recognition artefact in the automatic analysis of long–term electrocardiograms on time-domain measurement of heart rate variability. Med. Biol. Eng. Comput. 1993. Pp. 539-544.

4. Koronkevych O.I. Liniini dynamichni systemy pid diieiu vypadkovykh syl. Naukovi zapysky Lvivskoho universytetu. 1957. Vol. 44, 8. Pp. 175-183. [In Ukrainian].

5. Gladyshev E.G. Periodicheski i pochti periodicheski korrelirovannye sluchajnye processy s nepreryvnym vremenem. Teoriya veroyatnostej i eyo primeneniya. 1963. Vol. 2. Pp. 184-189. [In Russian].

6. Gudzenko L.I. O periodicheski nestacionarnyx processax. Radiotexnika i e'lektronika. 1959. Vol. 6. Pp. 1026-1064. [In Russian].

7. Vojchishin K.S., Dragan Ya.P. O prostoj stoxasticheskoj modeli estestvennyx ritmicheskix processov. Otbor i peredacha informacii. 1971. Vol. 29. Pp. 7-15. [In Russian].

8. Drahan Ya.P. Enerhetychna teoriia liniinykh modelei stokhastychnykh syhnaliv. Lviv: Tsentr stratehichnykh doslidzhen eko–biotekhnichnykh system. 1997. 361 p.

9. Yavorskij I.N. Statisticheskij analiz vektornyx periodicheski korrelirovannyx sluchajnyx processov. Otbor i peredacha informacii. Kiiv: Naukova dumka. 1987. Vol. 76. Pp. 3-12. [In Russian].

10. Yavorskij I.N. Statisticheskij analiz poli- i pochti periodicheski korrelirovannyx sluchajnyx processov. Otbor i obrabotka informacii. Kiev. 1989. Vol. 3 (79). Pp. 1-10. [In Russian].

11. Drahan Ya, Yevtukh P., Sikora L., Yavorskyi B. Periodychno korelovani vypadkovi protsesy yak adekvatni modeli syhnaliv kratnoi rytmiky pryrodnykh yavyshch i tekhnolohichnykh protsesiv. Kompiuterni tekhnolohii drukarstva. 2000. No. 4. Pp. 269-290. [In Ukrainian].

12. Myslovich M.V., Prijmak N.V., Shherbak L.N. Periodicheski korrelirovannye sluchajnye processy v zadachax obrabotki akusticheskoj informacii. K.: Znanie. 1980. 23 p. [In Russian].

13. Gardner W., Napolitano A., Paura L. Cyclostationarity: Half a century of research. Signal Processing. 2005. No. 86 (2006). Pp. 639-697.

14. Hurd H.L. Periodically Correlated Random Sequences: Spectral Theory and Practice. The University of North Carolina at Chapel Hill Hampton University.

15. Krasylnykov O.I., Marchenko B.H., Pryimak M.V. Protsesy z nezalezhnymy periodychnymy pryrostamy i periodychni bili shumy. Vidbir i obrobka informatsii. 1996. Vol. 10. Pp. 22-27. [In Ukrainian].

16. Kochel P. Periodically stationary Markovian decision models. Elektron. Informationsverarb. Kybernet. 1980. No. 16. Pp. 553-567. [In German].

17. Nematollahi A.R., Soltani A.R. Discrete time periodically correlated Markov processes. Probability and Mathematical Statistics. 2000. No. 20 (1). Pp. 127-140.

18. Ghysels E., McCulloch R.E., R.S. Tsay. Bayesian Inference for a General Class of Periodic Markov Switching Models. 1993.

19. Ghysels E. On the Periodic Structure of the Business Cycle. Cowles Foundation. Yale Universiti. 1992. No. 1028.

20. Bittanti S., Lorito F., Strada S. Markovian representations of cyclostationary processes, in: L. Gerencser, P.E. Caines (Eds.) Topics in Stochastic Systems: Modelling, Estimation and Adaptive Control. Springer, Berlin, Germany. 1991. Vol. 161. Pp. 31-46.

21. Marchenko B.H. Liniini periodychni protsesy. Pr. In.-tu elektrodynamiky NAN Ukrainy. Elektrotekhnika. 1999. Pp. 165-182. [In Ukrainian].

22. Pryimak M.V. Liniini vypadkovi polia z periodychnym porodzhuiuchym polem. Tekhnichna elektrodynamika. 1998. No. 3. Pp. 24-26. [In Ukrainian].

23. Lupenko S.A. Modeliuvannia ta metody obrobky tsyklichnykh syhnaliv sertsia na bazi liniinykh vypadkovykh funktsii. Avtoref. dys. … kand. tekhn. nauk: 01.05.02. Ternopilskyi derzhavnyi tekhnichnyi universytet imeni Ivana Puliuia. Ternopil. 2001. 20 p. [In Ukrainian].

24. Lupenko S.A., Pryimak M.V., Shcherbak L.M. Modeliuvannia liniinykh periodychnykh vypadkovykh protsesiv. Visnyk Ternopilskoho derzhavnoho tekhnichnoho universytetu. 2000. Vol. 5, no. 2. Pp. 97-103. [In Ukrainian].

25. Gonorovskij I.S. Radiotexnicheskie cepi i signaly. M.: Izd-vo "Sovetskoe radio". 1963. [In Russian].

26. Gordienko V.I., Zamora T.E., Luk'yanec G.V. Primenenie cifrovyx metodov obrabotki signalov v morskoj e'lektrorazvedke. Otbor i obrabotka informacii. 1988. Vol. 1. Pp. 86-89. [In Russian].

27. Harmuth H. Transmission of Information by Orthogonal Functions. New York, Heidelberg, Berlin: Springer, 1972. Edition 2.

28. Axmed N., Rao K.R. Ortogonal'nye preobrazovaniya pri obrabotke cifrovyx signalov: Per. s angl. M.: Svyaz'. 1980. 248 p.

29. Lyashenkov A.S. Sintezirovannyj kvaziperiodicheskij dvuxurovnevyj signal kak ideal'nyj meandr s peremennym periodom. Sbornik "Problemy radiosvyazi" GUP "Polet". N. Novgorod, 2002. [In Russian].

30. Pryimak M., Bodnarchuk I., Lupenko S. Umovno periodychni vypadkovi protsesy iz zminnym periodom. Visnyk Ternopilskoho derzhavnoho tekhnichnoho universytetu. Ternopil, 2005. Vol. 10, no. 2. Pp. 143-152. [In Ukrainian].

31. Lupenko S., Studena Yu. Matematychne modeliuvannia syhnaliv sertsia v zadachakh tekhnichnoi kardiometrii na bazi yikh modeli u vyhliadi tsyklichnoho vypadkovoho protsesu. Visnyk Ternopilskoho derzhavnoho tekhnichnoho universytetu. 2006. Vol. 11, no. 1. Pp. 134-142. [In Ukrainian].

32. Lupenko S.A., Lytvynenko Ya.V., Sverstiuk A.S. Statystychnyi sumisnyi analiz kardiosyhnaliv na osnovi vektora tsyklichnykh rytmichno poviazanykh vypadkovykh protsesiv. Elektronika ta systemy upravlinnia. Natsionalnyi aviatsiinyi universytet. 2008. No. 4 (18). Pp. 22-29. [In Ukrainian].

33. Horkunenko A.B., Lupenko S.A., Demianchuk N.R., Lytvynenko Ya.V. Imitatsiine modeliuvannia vzaiemopoviazanykh ekonomichnykh tsyklichnykh protsesiv na osnovi vektora tsyklichnykh rytmichno poviazanykh vypadkovykh protsesiv. Elektronika ta systemy upravlinnia. 2011. No. 2. Pp. 33-141. [In Ukrainian].

34. Lytvynenko I.V., Maruschak P.O., Lupenko S.A. Processing and modeling of ordered relief at the surface of heat-resistant steels after laser irradiation as a cyclic random process. Automatic Control and Computer Sciences. 2014. Vol. 48 (1). Pp. 1-9.

35. Lupenko S., Lutsyk N., Lapusta Y. Cyclic Linear Random Process As A Mathematical Model Of Cyclic Signals. Acta mechanica et automatica. 2015. No. 9 (4). Pp. 219-224.

Список використаної літератури

1. Лупенко, С.А. Теоретичні основи моделювання та опрацювання циклічних сигналів в інформаційних системах: наукова монографія [Текст] / С.А. Лупенко. – Львів: Видавництво «Магнолія 2006», 2016. – 344 с.

2. Сантопетро, Р.Ф. Происхождение и характеристики основного сигнала, шума и наводки в высокочастотной электрокардиограмме [Текст] / Р.Ф. Сантопетро // ТИИЭР. – 1977. – Т. 65, № 5. – С. 137 – 145.

3. Malik, M. Influence of the recognition artefact in the automatic analysis of long–term electrocardiograms on time–domain measurement of heart rate variability [Text] / M. Malik, R. Xia, O. Odemuyiwa // Med. Biol. Eng. Comput. – 1993. – P. 539 – 544.

4. Коронкевич, О.І. Лінійні динамічні системи під дією випадкових сил [Текст] / О.І. Коронкевич // Наукові записки Львівського університету. – 1957. – Т. 44, 8. – С. 175 – 183.

5. Гладышев, Е.Г. Периодически и почти периодически коррелированные случайные процессы с непрерывным временем [Текст] / Е.Г. Гладышев // Теория вероятностей и её применения. – 1963. – 8. – Вып. 2. – С. 184 – 189.

6. Гудзенко, Л.И. О периодически нестационарных процессах [Текст] / Л.И. Гудзенко // Радиотехника и электроника. – 1959. – 4. – Вып. 6. – С. 1026 – 1064.

7. Войчишин, К.С. О простой стохастической модели естественных ритмических процессов [Текст] / К.С. Войчишин, Я.П. Драган // Отбор и передача информации. – 1971. – Вып. 29. – С. 7 – 15.

8. Драган, Я.П. Енергетична теорія лінійних моделей стохастичних сигналів [Текст] / Я.П. Драган. – Львів: Центр стратегічних досліджень еко-біотехнічних систем, 1997. – 361 с.

9. Яворский, И.Н. Статистический анализ векторных периодически коррелированных случайных процессов [Текст] / И.Н. Яворский // Отбор и передача информации. – Киев: Наукова думка, 1987. – Вып. 76. – С. 3 – 12.

10. Яворский, И.Н. Статистический анализ поли- и почти периодически коррелированных случайных процессов [Текст] / И.Н. Яворский // Отбор и обработка информации. – Киев, 1989.– Вып. 3 (79). – С. 1 – 10.

11. Періодично корельовані випадкові процеси як адекватні моделі сигналів кратної ритміки природних явищ і технологічних процесів [Текст] / Я. Драган, П. Євтух, Л. Сікора, Б. Яворський // Комп'ютерні технології друкарства. – 2000. – № 4. – С. 269 – 290.

12. Мыслович, М.В. Периодически коррелированные случайные процессы в задачах обработки акустической информации [Текст] / М.В. Мыслович, Н.В. Приймак, Л.Н. Щербак. – К.: Знание, 1980. – 23 с.

13. Gardner, W.A. Cyclostationarity: Half a century of research [Text] / W.A. Gardner, A. Napolitano, L. Paura // Signal Processing. – 2005. – № 86 (2006). – P. 639 – 697.

14. Hurd, H.L. Periodically Correlated Random Sequences: Spectral Theory and Practice [Text] / H.L. Hurd, The University of North Carolina at Chapel Hill Hampton University.

15. Красильников, О.І. Процеси з незалежними періодичними приростами і періодичні білі шуми [Текст] / О.І. Красильников, Б.Г. Марченко, М.В. Приймак // Відбір і обробка інформації. – 1996. – Вип. 10. – С. 22 – 27.

16. Kochel, P. Periodically stationary Markovian decision models [Text] / P. Kochel // Elektron. Informationsverarb. Kybernet. – 1980. – No. 16. – P. 553 – 567. [In German].

17. Nematollahi, A.R. Discrete time periodically correlated Markov processes [Text] / A.R. Nematollahi, A.R. Soltani // Probability and Mathematical Statistics. – 2000. – No. 20 (1). – P. 127 – 140.

18. Ghysels, E. Bayesian Inference for a General Class of Periodic Markov Switching Models [Text] / E. Ghysels, R.E. McCulloch, R.S. Tsay. – 1993.

19. Ghysels, E. On the Periodic Structure of the Business Cycle [Text] / E. Ghysels // Cowles Foundation, Yale Universiti. – 1992. – No. 1028.

20. Bittanti, S. Markovian representations of cyclostationary processes, in: L. Gerencser, P.E. Caines (Eds.) [Text] / S. Bittanti, F. Lorito, S. Strada // Topics in Stochastic Systems: Modelling, Estimation and Adaptive Control. – Springer, Berlin, Germany. – 1991. – Vol. 161. – P. 31 – 46.

21. Марченко, Б.Г. Лінійні періодичні процеси [Текст] / Б.Г. Марченко // Пр. Ін.-ту електродинаміки НАН України. Електротехніка. – 1999. – С. 165 – 182.

22. Приймак, М.В. Лінійні випадкові поля з періодичним породжуючим полем [Текст] / М.В. Приймак // Технічна електродинаміка. – 1998. – № 3. – С. 24 – 26.

23. Лупенко, С.А. Моделювання та методи обробки циклічних сигналів серця на базі лінійних випадкових функцій: автореф. дис. … канд. техн. наук: 01.05.02 [Текст] / С.А. Лупенко. – Тернопільський державний технічний університет імені Івана Пулюя. – Тернопіль, 2001. – 20 с.

24. Лупенко, С.А. Моделювання лінійних періодичних випадкових процесів [Текст] / С.А. Лупенко, М.В. Приймак, Л.М. Щербак // Вісник Тернопільського державного технічного університету. – 2000. – Т. 5, № 2. – С. 97 – 103.

25. Гоноровский, И.С. Радиотехнические цепи и сигналы [Текст] / И.С. Гоноровский. – М.: Изд-во «Советское радио», 1963.

26. Гордиенко, В.И. Применение цифровых методов обработки сигналов в морской электроразведке [Текст] / В.И. Гордиенко, Т.Е. Замора, Г.В. Лукьянец // Отбор и обработка информации. – 1988. – Вып. 1. – С. 86 – 89.

27. Harmuth, H. Transmission of Information by Orthogonal Functions [Text] / H. Harmuth. – New York, Heidelberg, Berlin: Springer, 1972. – Edition 2.

28. Ахмед, Н. Ортогональные преобразования при обработке цифровых сигналов: пер. с англ. [Текст] / Н. Ахмед, К.Р. Рао. – М.: Связь, 1980. – 248 с.

29. Ляшенков, А.С. Синтезированный квазипериодический двухуровневый сигнал как идеальный меандр с переменным периодом [Текст] / А.С. Ляшенков // Сборник «Проблемы радиосвязи» ГУП «Полет». – Н. Новгород, 2002.

30. Приймак, М. Умовно періодичні випадкові процеси із змінним періодом [Текст] / М. Приймак, І. Боднарчук, С. Лупенко // Вісник Тернопільського державного технічного університету. – Тернопіль, 2005. – Т. 10, № 2. – С. 143 – 152.

31. Лупенко, С. Математичне моделювання сигналів серця в задачах технічної кардіометрії на базі їх моделі у вигляді циклічного випадкового процесу [Текст] / С. Лупенко, Ю. Студена // Вісник Тернопільського державного технічного університету. – 2006. – Т. 11, № 1. – С. 134 – 142.

32. Лупенко, С.А. Статистичний сумісний аналіз кардіосигналів на основі вектора циклічних ритмічно пов'язаних випадкових процесів [Текст] / С.А. Лупенко, Я.В. Литвиненко, А.С. Сверстюк // Електроніка та системи управління. Національний авіаційний університет. – 2008. – № 4 (18). – С. 22 – 29.

33. Горкуненко, А.Б. Імітаційне моделювання взаємопов'язаних економічних циклічних процесів на основі вектора циклічних ритмічно пов'язаних випадкових процесів [Текст] / А.Б. Горкуненко, С.А. Лупенко, Н.Р. Дем'янчук, Я.В. Литвиненко // Електроніка та системи управління. – 2011. – № 2. – С. 133 – 141.

34. Lytvynenko, I.V. Processing and modeling of ordered relief at the surface of heat-resistant steels after laser irradiation as a cyclic random process [Text] / I.V. Lytvynenko, P.O. Maruschak, S.A. Lupenko // Automatic Control and Computer Sciences, – 2014. – Vol. 48 (1). – P. 1 – 9.

35. Lupenko, S. Cyclic Linear Random Process As A Mathematical Model Of Cyclic Signals [Text] / S. Lupenko, N. Lutsyk, Y. Lapusta // Acta mechanica et automatica – 2015. – № 9 (4). – Pp. 219 – 224.

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ПОРІВНЯЛЬНИЙ АНАЛІЗ МАТЕМАТИЧНИХ МОДЕЛЕЙ СИГНАЛІВ ТА ПРОЦЕСІВ ЦИКЛІЧНОЇ СТРУКТУРИ

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Резюме. *З метою дослідження потенціалу, перспектив та ефективності використання відомих математичних моделей циклічних сигналів та процесів як фундаменту математичного забезпечення інформаційних систем, їх аналізу, прогнозування та імітації, проведено компаративний аналіз широкого класу математичних об'єктів, що використовуються або можуть бути використані як моделі сигналів та процесів циклічної структури. Проведене аналітичне дослідження допоможе досліднику обґрунтовано вибрати та адаптувати (адекватно структурі досліджуваних сигналів та задачам дослідження) математичну модель із наявної їх сукупності, що суттєво підвищить ефективність (спростить та пришвидшить) розбудови математичного забезпечення проектованої інформаційної системи.*

Ключові слова: *циклічні сигнали, циклічні процеси, математичні моделі, компаративний аналіз.*

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