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A NOVEL COMBINED CHAOS-GEOMETRIC AND VIBRATION BLIND SOURCE MONITORING APPROACH TO DAMAGE ANALYSIS AND DETECTION OF ENGINEERING STRUCTURES (NUCLEAR REACTORS) UNDER VARYING ENVIRONMENTAL, OPERATIONAL CONDITIONS AND EMERGENCY ACCIDENTS

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A NOVEL COMBINED CHAOS-GEOMETRIC AND VIBRATION BLIND SOURCE MONITORING APPROACH TO DAMAGE ANALYSIS AND DETECTION OF ENGINEERING STRUCTURES (NUCLEAR POWER PLANTS) UNDER VARYING ENVIRONMENTAL, OPERATIONAL CONDITIONS AND EMERGENCY ACCIDENTS

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Abstract. The paper is devoted to problem of analysis, identification and prediction of the presence of damages, which above a certain level may present a serious threat to the engineering (vibrating) structures such as different technical systems and devices, including nuclear reactors etc in result of the operational, environmental conditions, including the emergency accidents. For the first time we present and apply a novel computational approach to modelling, analysis (further prediction) of a chaotic behaviour of structural dynamic properties of the engineering structures, based on earlier developed chaos-geometric and vibration blind source monitoring approach. In the concrete realization the novel approach includes a combined group of blind source monitoring , non-linear analysis and chaos theory methods such as a correlation integral approach, average mutual information, surrogate data, false nearest neighbours algorithms, the Lyapunov's exponents and Kolmogorov entropy analysis, nonlinear prediction models etc. As illustration we present the results of the numerical investigation of a chaotic elements in dynamical parameter time series for the experimental cantilever beam (the forcing and environmental conditions are imitated by the damaged structure, the variable temperature and availability of the pink-noise force). Using numerical time series analysis results, we list the data on the topological and dynamical invariants, namely, the correlation, embedding, Kaplan-Yorke dimensions, the Lyapunov's exponents and Kolmogorov entropy etc and consider a construction of the engineering structures (including nuclear reactors) damage detection prediction model. Under an influence of the operational, environmental conditions, including the emergency incidents (accidents) during the operation of the nuclear reactor vessel it is more than probable development (growth) of damages (defects) that existed initially, as well as the emergence of new defects and their further development (growth). In this case technical application of vibration diagnostics technologies and further analysis within the presented approach could be very useful together with available probabilistic models for assessing the safety of nuclear reactors.

Keywords: damages of engineering (vibrating) structures, nuclear power plants, new mathematical models, new microsystem technology, chaos-geometric approach

НОВИЙ КОМБІНОВАНИЙ ХАОС-ГЕОМЕТРИЧНИЙ ПІДХІД І BLIND SOURCE МОНІТОРИНГ ДО АНАЛІЗУ І ДЕТЕКТУВАННЯ УШКОДЖЕНЬ ІНЖЕНЕРНИХ СТРУКТУР (ЯДЕРНІ РЕАКТОРИ) ПРИ ЗМІНІ ЕКСПЛУАТАЦІЙНИХ УМОВ, УМОВ НАВКОЛИШНЬОГО СЕРЕДОВИЩА, АВАРІЙНИХ ІНЦИДЕНТІВ

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Анотація. Стаття присвячена проблемі аналізу, ідентифікації та прогнозування наявності пошкоджень, які вище певного рівня можуть представляти серйозну загрозу для інженерних (вібраційних) структур, таких як різні технічні системи та пристрої, включаючи ядерні реактори і т.д., внаслідок зміни експлуатаційних, екологічних умов, аварійних інцидентів. Вперше ми представляємо і застосовуємо новий обчислювальний підхід до моделювання, аналізу (подальшого прогнозування) хаотичного поведінки структурно-динамічних властивостей інженерних структур на основі раніше розробленого нами хаосу-геометричного методу плюс blind source моніторинг. У конкретної реалізації новий підхід включає в себе об'єднану групу методів та алгоритмів нелінійного аналізу і теорії хаосу, таких як метод кореляційного інтеграла та середньої взаємної інформації, алгоритми помилкових найближчих сусідів та сурогатних даних, аналіз на основі показників Ляпунова та ентропії Колмогорова, моделі нелінійного прогнозування і т. і. В якості ілюстрації наведені результати чисельного дослідження хаотичних елементів в часових рядах динамічних параметрів для експериментального консольного пучка (вплив і умови навколишнього середовища імітуються ушкодженою структурою, змінною температурою і наявністю сили типу рожевого шуму). На основі аналізу чисельних часових рядів отримані дані про топологічні і динамічні инваріанти, а саме: кореляційну розмірність, розмірності вкладення, Каплана-Йорка, показники Ляпунова, ентропію Колмогорова і т.і., та розглянута конструкція моделі прогнозування і виявлення пошкоджень інженерних споруд, у т.ч., ядерних реакторів. Під впливом експлуатаційних, екологічних умов, у тому числі надзвичайних інцидентів (аварій) під час експлуатації корпуса ядерного реактора є більш, ніж імовірним розвиток (зростання) шкодувань (дефектів), що існували спочатку, а також виникнення нових дефектів та їх подальший розвиток (зростання). У цьому випадку технічне застосування вібраційно-діагностичних технологій та подальший аналіз в рамках розвинутого в роботі підходу можуть бути дуже корисними разом із існуючими імовірнісними моделями оцінки безпеки ядерних реакторів.

Ключові слова: пошкодження інженерних (вібраційних) споруд, атомні реактори, нові математичні моделі, нова мікросистемна технологія, хаос-геометричний підхід

НОВЫЙ КОМБИНИРОВАННЫЙ ХАОС-ГЕОМЕТРИЧЕСКИЙ ПОДХОД И BLIND SOURCE МОНИТОРИНГ К АНАЛИЗУ И ДЕТЕКТИРОВАНИЮ ПОВРЕЖДЕНИЙ ИНЖЕНЕРНЫХ СТРУКТУР (ЯДЕРНЫЕ РЕАКТОРЫ) ПРИ ИЗМЕНЕНИИ ЭКСПЛУАТАЦИОННЫХ УСЛОВИЙ, УСЛОВИЙ ОКРУЖАЮЩЕЙ СРЕДЫ, АВАРИЙНЫХ ИНЦИДЕНТОВ

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Аннотация. Статья посвящена проблеме анализа, идентификации и прогнозирования наличия повреждений, которые выше определенного уровня могут представлять серьезную угрозу для инженерных (вибрационных) структур, таких как различные технические системы и устройства, включая ядерные реакторы и т.д., вследствие изменения эксплуатационных, экологических условий, аварийных инцидентов. Впервые мы представляем и применяем новый вычислительный подход к моделированию, анализу (дальнейшему прогнозированию) хаотического поведения структурно-динамических свойств инженерных структур на основе ранее разработанного нами хаоса-геометрического метода плюс известный blind source мониторинг. В конкретной реализации новый подход включает в себя объединенную группу методов и алгоритмов нелинейного анализа и теории хаоса, таких как метод корреляционного интеграла и средней взаимной информации, алгоритмы ложных ближайших соседей и суррогатных данных, анализ на основе показателей Ляпунова и энтропии Колмогорова, модели нелинейного прогнозирования и т. д. В качестве иллюстрации приведены результаты численного исследования хаотических элементов в временных рядах динамических параметров для экспериментального консольного пучка (воздействие и условия окружающей среды имитируются поврежденной структурой, переменной температурой и наличием силы типа розового шума). На основе численного анализа временных рядов получены данные о топологических и динамических инвариантах, а именно: корреляционной размерности, размерностях вложения, Каплана-Йорка, показателях Ляпунова, энтропии Колмогорова и т.д., и рассмотрена конструкция модели прогнозирования и обнаружения повреждений инженерных сооружений, в т.ч., ядерных реакторов. Под влиянием эксплуатационных, экологических условий, в том числе чрезвычайных инцидентов (аварий) при эксплуатации корпуса ядерного реактора является более чем вероятным развитие (рост) возмещений (дефектов), существовавшие изначально, а также возникновение новых дефектов и их дальнейшее развитие (рост). В этом случае техническое применение вибрационно-диагностических технологий и последующий анализ в рамках развитого в работе подхода могут быть очень полезными вместе с использованием существующих вероятностных моделей оценки безопасности ядерных реакторов.

Ключевые слова: повреждения инженерных (вибрационных) сооружений, атомные реакторы, новые математические модели, новая микросистемная технология, хаос-геометрический подход

1. Introduction

In the last decade the problem of analysis, identification and further prediction of the presence of damages (cracks) in different engineering (vibrating) structures (such as different mechanical and hydrotechnical systems, devices, equipment, turbochargers, engines of hydroelectrical stations, atomic reactors etc) because of the changing operational, environmental conditions, including the emergency accidents, attracts an increasing interest and has a great importance [1-4]. The standard way is using so called structural health monitoring (SHM) methods (see [4]) that have been intensively investigated over the last decades and allow the early identification and further localization of damages. Usually change of structural dynamic properties due to environmental, operational and other (earthquakes, tsunamis, emergency explosions etc) incidents results in the existence, location and size of damages. Really, the changing conditions such as temperature, moisture, pressure, mechanical actions etc may cause significant changes in their properties and result in the damage detection algorithms to false decisions. The useful information regarding the effects of environmental and operational conditions on a dynamics of different structures can be found in Ref. [4].

Let us remind that severe accidents in 1986 ar the Chernobyl and in 2011 at 1 ÷ 4 Fukushima-Daiichi nuclear power plans and a series of incidents and accidents at a number of power units of other nuclear power plants in different countries of the world revealed a limited limit to the generally accepted approaches to the analysis and assessment of the safety of nuclear power plants in operation and projected. For example, all the Chernobyl and Fukushima-Daiichi emergency power units met the specified probabilistic safety criteria, but avoided a major accident (maximum level 7 on the IAEA scale) that had catastrophic environmental consequences, however, failed. As it has been noted in many Refs. (see, for example, [2] and Refs. therein), the nuclear accident at the Fukushima-Daiichi nuclear power plant was a consequence of the joint emergence of several external extreme off-project environmental (indeed, geophysical) impacts on nuclear power plants, accompanied by catastrophic violations of technological processes: a complete loss of long-term energy supply to the main and auxiliary equipment of power units, gas vapor explosions in reactor plants, and others. However, in the generally accepted approaches (assessments) to the security analysis, based on the ranking (ranking) of the estimates of the probability of occurrence of emergency events, the contribution to relatively unlikely emergency events in the integral safety indicators is given insufficient attention. Violation of the normal operation of a nuclear reactor due to failure due to unlikely emergency environmental or operational conditions of any element of the nuclear reactor may change the values of temperature, velocity and other parameters of the coolant in comparison with the values corresponding stable normal operating conditions of the nuclear reactor.

In the light of saying, a great interest attracts carrying out an effective consistent approaches to modelling, analysis (further prediction) of a chaotic behaviour of structural dynamic properties of the engineering structures. It is worth to note that an especial interest attracts the point-wise summation of similar Wavelet Transform Modulus Maxima decay lines, which has been used in [4] to detect the damages under varying environmental and operational conditions. This damage detection methodology has been applied to investigation of both a simulated 3 degrees-of-freedom system and an experimental cantilever beam, excited by white and pink noise forces. The master conclusion [4] is that that the SHM methodology applied is capable of identifying the presence of damage in a time range under varying environmental and/or operational conditions. This is fully confirmed by an effective application of the methodology to experimental data, to verify its ability in identifying the presence of damage in real-life operations. Sadhu and Hazre [4] presented a novel damage detection algorithm based on blind source separation in conjunction with time-series analysis. Blind source separation (BSS), is a powerful signal processing tool that is used to identify the modal responses and mode shapes of a vibrating structure using only the knowledge of responses. In the proposed method [4], BSS is first employed to estimate the modal response using the vibration measurements. Time-series analysis is then performed to characterize the mono-component modal responses and successively the resulting time-series models are utilized for one-step ahead prediction of the modal response. From experimental viewpoint, especially valuable are now methods of nondestructive testing, in particular, vibrodiagnostics (see details in Refs. [1-4]). Each class and even each type of equipment is characterized by its own separate sets of criteria for assessing the vibration state, depending on the conditions of assembly, installation, operation, etc. A certain one-sidedness of the vibrodiagnostic methods, based primarily on the primary Fourier transform of the signal, does not allow for an integrated approach to solving the problem. The wide spread and more advanced methodologies such as wavelet analysis, subspace-based identification methodologies, regression analysis, singular value decomposition, auto-associative neural network and factor analysis under situation, dyanical systems and chaos theory methods [5-10] etc have been discussed.

In this paper for the first time we present and apply a novel computational approach to modelling, analysis (further prediction) of a chaotic behaviour of structural dynamic properties of the engineering structures, based on earlier developed chaos-geometric and vibration blind source monitoring approach. In the concrete realization the novel approach includes a combined group of blind source monitoring , non-linear analysis and chaos theory methods such as a correlation integral approach, average mutual information, surrogate data, false nearest neighbours algorithms, the Lyapunov's exponents and Kolmogorov entropy analysis, nonlinear prediction models etc [5-11]. As illustration we present the results of the numerical investigation of a chaotic elements in dynamical parameter time series for the experimental cantilever beam (the forcing and environmental conditions are imitated by the damaged structure, the variable temperature and availability of the pink-noise force). Using numerical time series analysis results, we list the data on the topological and dynamical invariants, namely, the correlation, embedding, Kaplan-Yorke dimensions, the Lyapunov's exponents and Kolmogorov entropy etc and consider a construction of the engineering structures (including nuclear reactors) damage detection prediction model. All calculations are performed with using "Geomath", "Superatom" and "Quantum Chaos" computational codes [11-16]. The possibilities of using the proposed approach under studying the nuclear reactors security are in frief considered.

2. Chaos-geometric and blind source separation monitoring algorithms to damage analysis and detection for engineering structures

The blind source separation (BSS) methods have emerged as a powerful class of signal processing methods capable of monitoring the health of a large class of engineering structures. Many concrete applied results (for example, see [4] and Refs. there in). reveal the potential of using the principle of BSS for a wide range of structural engineering problems. Originally proposed for a fewer class of problems involving broadband excitations, static mixtures, and relatively large sensor densities, BSS extensions to underdetermined case, nonstationary environment, decentralized sensing network, and for convolutive mixing have also been reported in recent studies by many authors. Note that in ref. [4] it has been in details presented a novel time-series analysis based BSS method and applied to tackle damage detection in civil structures which is commonly encountered as a major structural health monitoring problem. Our idea is in combimation of the BBS algorithm by Sadhu-Hazra and chaos-geometric (chaos-dynamnical) approach, which has been earlier developed by us. The key elements of the chaos-geometric computational approach to studying the complex non-linear systems time series with elements of a chaos are presented in Refs. [5-11], so below we are limited only by the key ideas.

Let us note that for the first time idea to apply the approach [7-11] to damage detection in the engineering structure has been proposed in [7]. In our case the displacement quantity is described by some scalar series $s(n)=s(t_0+ n\Delta t) = s(n)$, where t_0 is a start time, Δt is time step, and n is number of the values measurements (in whole we considered a series of consisting of a total of a ~10^4 data points). The main task is to reconstruct phase space using as well as possible information contained in $s(n)$. To do it, the method of using time-delay coordinates by Packard et al [5] is used. The direct using lagged variables $s(n+\tau)$ (here τ is some integer to be defined) results in a coordinate system where a structure of orbits in phase space can be captured. A set of time lags is used to create a vector in d dimensions,

$$\mathbf{y}(n)= [s(n), s(n + \tau), s(n + 2\tau), .., s(n +(d–1)\tau)], \quad (1)$$

the required coordinates are provided. Here the dimension d is the embedding dimension, d_E.

To determine the proper time lag at the beginning one should use the known method of the linear autocorrelation function $C_L(\delta)$ and look for that time lag where $C_L(\delta)$ first passes through 0. The alternative additional approach is provided by the method of average mutual information as an approach with so called nonlinear concept of independence.

According to Takens and Mañé (see, for example [5]), any time lag will be acceptable is not terribly useful for extracting physics from data. If τ is chosen too small, then the coordinates $s(n + j\tau)$ and $s(n + (j + 1)\tau)$ are so close to each other in numerical value that they cannot be distinguished from each other. Similarly, if τ is too large, then $s(n + j\tau)$ and $s(n + (j + 1)\tau)$ are completely independent of each other in a statistical sense. Also, if τ is too small or too large, then the correlation dimension of attractor can be under- or overestimated respectively. It is therefore necessary to choose some intermediate (and more appropriate) position between above cases. The first wide spread approach is to compute the linear autocorrelation function

$$C_L(\delta) = \frac{\frac{1}{N}\sum_{m=1}^{N}[s(m+\delta)-\bar{s}][s(m)-\bar{s}]}{\frac{1}{N}\sum_{m=1}^{N}[s(m)-\bar{s}]^2}, \quad (2)$$

where $\bar{s} = \frac{1}{N}\sum_{m=1}^{N} s(m)$

and to look for that time lag where $C_L(\delta)$ first passes through zero. This gives a good hint of choice for τ at that $s(n + j\tau)$ and $s(n + (j + 1)\tau)$ are linearly independent. However, a linear independence of two variables does not mean that these variables are nonlinearly independent since a nonlinear relationship can differs from linear one. It is therefore preferably to use an approach with a nonlinear concept of independence, e.g. the average mutual information. Briefly, the concept of mutual information can be described as follows. Let there are two systems, A and B, with measurements a_i and b_k. The amount one learns in bits about a measurement of a_i from a measurement of b_k is given by the arguments of information theory as

$$I_{AB}(a_i,b_k) = \log_2\left(\frac{P_{AB}(a_i,b_k)}{P_A(a_i)P_B(b_k)}\right), \quad (3)$$

where the probability of observing a out of the set of all A is $P_A(a_i)$, and the probability of finding b in a measurement B is $P_B(b_i)$, and the joint probability of the measurement of a and b is $P_{AB}(a_i, b_k)$. The mutual information I of two measurements a_i and b_k is symmetric and non-negative, and equals to zero if only the systems are independent. The average mutual information between any value a_i from system A and b_k from B is the average over all possible measurements of $I_{AB}(a_i, b_k)$,

$$I_{AB}(\tau) = \sum_{a_i,b_k} P_{AB}(a_i,b_k) I_{AB}(a_i,b_k) . \quad (4)$$

To place this definition to a context of observations from a certain physical system, let us think of the sets of measurements $s(n)$ as the A and of the measurements a time lag τ later, $s(n + \tau)$, as B set. The average mutual information between observations at n and $n + \tau$ is then

$$I_{AB}(\tau) = \sum_{a_i,b_k} P_{AB}(a_i,b_k) I_{AB}(a_i,b_k) . \quad (5)$$

Now we have to decide what property of $I(\tau)$ we should select, in order to establish which among the various values of τ we should use in making the data vectors $\mathbf{y}(n)$. It is worth to remind that the autocorrelation coefficient failed to achieve zero, i.e. the autocorrelation function analysis not provides us with any value of τ. Such an analysis can be certainly extended to values exceeding 1000, but it is known that an attractor cannot be adequately reconstructed for very large values of τ. The mutual information function usually exhibits an initial rapid decay (up to a lag time of about 10) followed more slow decrease before attaining near-saturation at the first minimum. In fact the autocorrelation function and average mutual information can be considered as analogues of the linear redundancy and general redundancy, respectively, which was applied in the test for nonlinearity.

The further next step is to determine the embedding dimension, d_E, and correspondingly to reconstruct a Euclidean space R^d large enough so that the set of points d_A can be unfolded without ambiguity. The dimension, d_E, must be greater, or at least equal, than a dimension of attractor, d_A, i.e. $d_E > d_A$. To reconstruct the attractor dimension (see details in [5-9]) and to study the signatures of chaos in a time series, one could use different methods, however, the most effective ones are represented by the correlation integral algorithm of Grassberger and Procaccia and the false nearest neighbours by Kennel et al (see details in [7]).

The principal question of studying any complex system with a non-linear chaotic dynamics is to build the corresponding prediction model and define how predictable is a chaotic system. At preliminary step it means the obligatory determination of such characteristics as the Kolmogorov entropy (and correspondingly the predictability measure as it can be estimated by the Kolmogorov entropy), the Lyapunov's exponents, by the Kaplan and Yorke dimension.

Let us remind that according to the standard definition, the Lyapunov's exponents are usually defined as asymptotic average rates and they are related to the eigenvalues of the linearized dynamics across the attractor. Naturally, the knowledge of the whole spectrum of Lyapunov's exponents allows to determine other important invariants such as the Kolmogorov entropy and the attractor's dimension. The Kolmogorov entropy is determined by the sum of the positive Lyapunov exponents. The estimate of the dimension of the attractor is provided by the Kaplan and Yorke conjecture

$$d_L = j + \sum_{i=1}^{j} \lambda_i / |\lambda_{j+1}|, \qquad (6)$$

where j is such that $\sum_{i=1}^{j} \lambda_i > 0$ and $\sum_{i=1}^{j+1} \lambda_i < 0$, and the Lyapunov exponents are taken in descending order. The fundamental ideas for building the possible prediction models for non-linear systems with a chaotic elements can be found in Refs. [7-10], however, so below we are limited only by key ideas and concrete computing the topological and dynamical invariants for the engineering system. The key idea of the prediction model can be based on using the traditional concept of a compact geometric attractor in which evolves the measurement data, plus the implementation of neural network algorithms [7-10]. The existing so far in the theory of chaos prediction models are based on the concept of an attractor.

The meaning of the concept is in fact a study of the evolution of the attractor in the phase space of the system and, in a sense, modelling («guessing») time-variable evolution. In the phase space of the system an orbit continuously rolled on itself due to the action of dissipative forces and the nonlinear part of the dynamics, so it is possible to stay in the neighborhood of any point of the orbit *y (n)* other points of the orbit y^r *(n), r = 1, 2, ...,* N_B, which come in the neighborhood *y (n)* in a completely different times than n. Of course, then one could try to build different types of interpolation functions that take into account all the neighborhoods of the phase space and at the same time explain how the neighborhood evolve from *y (n)* to a whole family of points about *y (n+1)*. Use of the information about the phase space in the simulation of the evolution of some engineering structure in time can be regarded as a fundamental element in the simulation of random processes. Considering the neural network (in this case, the appropriate term "engineering structure" neural network) with a certain number of neurons, as usual, we can introduce the operators S_{ij} synaptic neuron to neuron u_i u_j, while the corresponding synaptic matrix is reduced to a numerical matrix strength of synaptic connections: W = | | w_{ij} | |. The operator is described by the standard activation neuro-equation determining the evolution of a neural network in time:

$$s_i' = sign(\sum_{j=1}^{N} w_{ij} s_j - \theta_i) \cdot \qquad (7)$$

From the point of view of the theory of chaotic dynamical systems, the state of the neuron (the chaos-geometric interpretation of the forces of synaptic interactions, etc.) can be represented by currents in the phase space of the system and its the topological structure is obviously determined by the number and position of attractors.

These idea have been used in order to make more advanced the wide spread prediction model which is based on the constructing a parameterized nonlinear function F (x, a), which transform y (n) to y (n + 1) = F (y (n), a), and then using different criteria for determining the parameters a. The most common form of the local model is very simple (more complicated and exact versions can be used [7]):

$$s_i^{'} = sign(\sum_{j=1}^{N} w_{ij} s_j - \theta_i), \quad (8)$$

where Δn - the time period for which forecasting should be done.

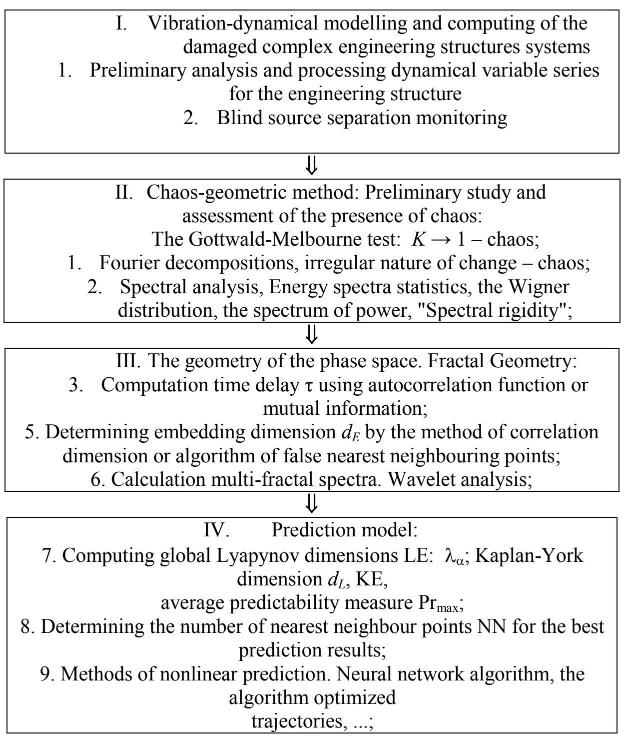


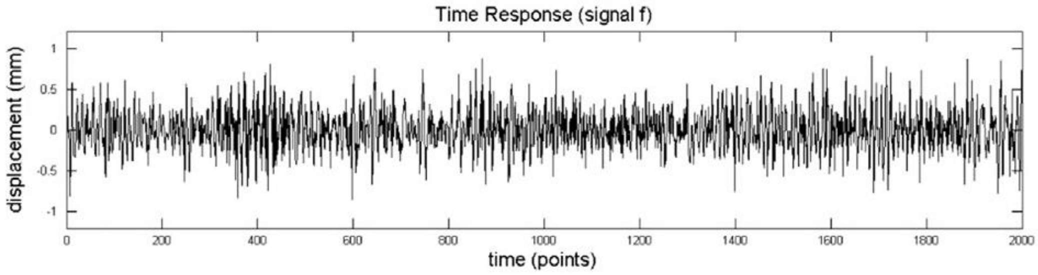
Figure 1. Flowchart of the proposed combined vibration-dynamical and chaos-geometric approach to nonlinear analysis and prediction of chaotic dynamics, damage detection and locations of the complex engineering structures.

The coefficients $a_j^{(k)}$, may be determined by a least-squares procedure, involving only points $s(k)$ within a small neighbourhood around the reference point. Thus, the coefficients will vary throughout phase space. The fit procedure amounts to solving (d_A + 1) linear equations for the (d_A + 1) unknowns. One could create a model of the process occurring in the neighborhood, at the neighborhood and by combining together these local models to construct a global nonlinear model that describes most of the structure of the attractor. In order to get more advanced prediction of chaotic dynamics one may apply the polynomial model with using the neural network algorithm [7-11]. Obviously, such a model will do for any engineering structure, including nuclear reactors and others (under availibilty of the corresponding vinbratin monitoring data).

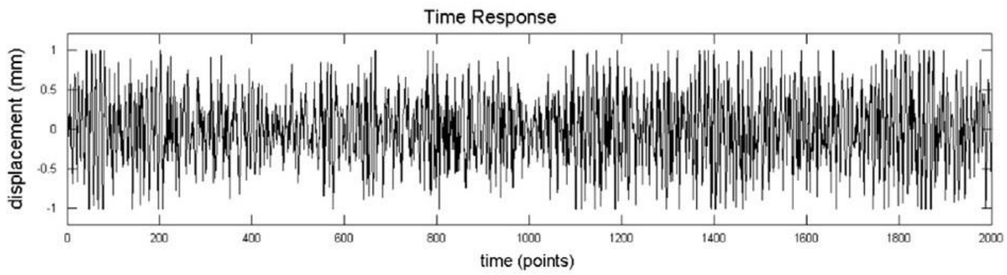
In Figure 1 we present the flowchart of the combined vibration-dynamical and chaos-geometric approach to nonlinear analysis and prediction of chaotic dynamics, damage detection and locations of the complex engineering structures ([7-10]).

3. The numerical results and conclusions

As illustration we present the results of the numerical investigation of a chaotic elements in dynamical parameter time series for the experimental cantilever beam (the forcing and environmental conditions are imitated by the damaged structure, the variable temperature and availability of the pink-noise force) [4]. As the initial data we use the data of the corresponding cantilever beam (excited by white and pink noise forces) time domain response series [4]. The detailed description of the experimental setup of a cantilever beam is presented in Ref. [4]. Here we only note that it consists of steel having the following dimensions: length 592 mm, width 30 mm, and thickness 1.5 mm, a density of 7.87×10^{-6} kg/mm^3, Young modulus of 200×10^6 mN/mm^2, and second moment of area of 8.44 mm^4. The electrodynamic shaker was used to excite the cantilever beam and it was connected to the beam via a stringer rod to minimize the interaction between the shaker and the structure. Figure 2 shows the the typical experimental cantilever beam time domain response series under the definite environmental and forcing conditions (the series is related to the case of the damaged structure, the variable temperature and availability of the pink-noise force). Other situations are analyzed in Ref.[4].



(a)



(b)

Figure 2. The experimental cantilever beam time domain response series for the case: (a) damaged structure, constant temperature and availability of the pink-noise force; (b) damaged structure, variable temperature and availability of the pink-noise force (see text).

In table 1 we list data on the time delay (τ), depending on the different values of the autocorrelation function (C_L) and the first minimum of mutual information (I_{min1}) for the studied time domain response series in a case of the damaged structure, the variable temperature and availability of the pink-noise force. In Table 1 we фдіщ list correlation exponents (d_2) and embedding dimensions determined by false nearest neighbours method (d_N) with percentage of false neighbours (in parentheses).

Table 1

The values of the time delay (lag), depending on the different values of the autocorrelation function (C_L) and the first minimum of mutual information (I_{min1}), Correlation exponents (d_2) and embedding dimensions determined by false nearest neighbours method (d_N) with percentage of false neighbours (in parentheses) calculated for various time lags (τ) for the studied time series (see text)

$C_L = 0$	τ=114	d_2	d_N
$C_L = 0.1$	τ=68	7.68	9 (9.1)
$C_L = 0.5$	τ=6	5.45	6 (1.3)
I_{min1}	τ=9	5.48	6 (1.3)

The Table 2 summarizes the results of the computational reconstruction of the attractors (the correlation dimension (d_2), embedding dimension (d_E), the first two Lyapunov's exponents (λ_1 and λ_2), the Kaplan-Yorke dimension (d_L), as well as the Kolmogorov entropy (K_{entr}), and average limit of predictability (Pr_{max}). Analysis of the obtained data shows that the correlation exponent *d* attains saturation with an increase in the embedding dimension, and the system is generally considered to exhibit chaotic elements. The saturation value of the correlation exponent is defined as the correlation dimension (d_2) of the attractor. The similar data for a reconstruction of the attractor dimension have been obtained by using the alternative false nearest neighbouring points method (version [11]). The dimension of the attractor is defined as the embedding dimension, in which the number of false nearest neighbouring points was less than 3%.

Table 2

Correlation dimension (d_2), embedding dimension (d_E), first two Lyapunov exponents (λ_1 and λ_2), Kaplan-Yorke dimension (d_L), the Kolmogorov entropy (K_{entr}), average limit of predictability (Pr_{max})

d_2	d_E	λ_1	λ_2	d_L	K_{entr}	Pr_{max}
5.45	6	0.0197	0.0061	3,98	0.026	39

The Kaplan-Yorke dimension is less than the embedding dimension that confirms the correct choice of the latter. The presence of the two positive λ_i suggests the conclusion above regarding presence of the chaotic elements.

Further let us give the qualitative consideration of the perspectives of application of the approach to studying the possible damages in the nuclear reactor vessels. It is well kwnon (dor example, look [9-11]), that the constructive steel of the nuclear reactor vessels in the initial state have a set of qualities that allow them to be considered as homogeneous and isotropic. The modulus of elasticity and the Poisson coefficient characterize the macroscopic properties of the material, that is, they take into account the influence of microdefects that are found in the investigated material. Under an influence of the operational, environmental conditions, including the emergency incidents (accidents) during the operation of the reactor vessel it is more than probable the development (growth) of damages (defects) that existed initially, as well as the emergence of new defects and their further development (growth). Naturally, during some time these processes of defect changes in the material lead to a significant change in its properties. For example, as it isin details considred in Ref. [10], the directed action of an operating load (for example, internal pressure) can lead to the fact that the material isotropic in the initial state acquires the properties of anisotropic. Moreover, an anisotropy, acquired as a result of defects in the material, in turn, has a noticeable effect on the thermal conductivity and stress-strain state. In a case of the emergency events such as earthquakes, tsunamis other incidents these processes discussed could accept very dangerous form. This fact necessitates the studying the laws of the influence of microdefects on the properties of structural materials of the nuclear reactor vessel, in more details, technical application of vibration diagnostics technologies and further analysis within the presented approach. In our opinion such an approach could be very useful together with available probabilistic models for assessing the safety of nuclear reactors.

To conclude, we have considered a problem of analysis, identification and prediction of the presence of damages, which above a certain level may present a serious threat to the engineering (vibrating) structures such as different technical systems and devices, including nuclear reactors etc in result of the operational, environmental conditions, including the emergency accidents. Starting from earlier developed chaos-geometric and the known vibration blind source monitoring algorithms we presented a novel computational approach to modelling, analysis (further prediction) of a chaotic behaviour of structural dynamic properties of the engineering structures. In the concrete realization the novel approach includes a combined group of blind source monitoring , non-linear analysis and chaos theory methods such as a correlation integral approach, average mutual information, surrogate data, false nearest neighbours algorithms, the Lyapunov's exponents and Kolmogorov entropy analysis, nonlinear prediction models etc. The structure, character and dynamical and topological parameters can be different from each other, which made it possible in the future to relate the invariants of real signals to the attractors of «elementary» signals and determine the nature of the defect. As a result of analysis of reconstructed attractors on the basis of real signals, a qualitative conclusion can be drawn about the presence and development of prevailing defects in a system and to predict how close the state of the system is to the critical one.

The results of the numerical investigation of a chaotic elements in dynamical parameter time series for the experimental cantilever beam (the forcing and environmental conditions are imitated by the damaged structure, the variable temperature and availability of the pink-noise force) are pesented as illustration. Using numerical time series analysis results, the data on the topological and dynamical invariants, namely, the correlation, embedding, Kaplan-Yorke dimensions, the Lyapunov's exponents and Kolmogorov entropy etc are presented. The possibilities of using the proposed approach under studying the nuclear reactors security is in frief considered.

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A NOVEL COMBINED CHAOS-GEOMETRIC AND VIBRATION BLIND SOURCE MONITORING APPROACH TO DAMAGE ANALYSIS AND DETECTION OF ENGINEERING STRUCTURES (NUCLEAR REACTORS) UNDER VARYING ENVIRONMENTAL, OPERATIONAL CONDITIONS AND EMERGENCY ACCIDENTS

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Summary

The paper is devoted to problem of analysis, identification and prediction of the presence of damages, which above a certain level may present a serious threat to the engineering (vibrating) structures such as different technical systems and devices, including nuclear reactors etc in result of the operational, environmental conditions, including the emergency accidents. For the first time we present and apply a novel computational approach to modelling, analysis (further prediction) of a chaotic behaviour of structural dynamic properties of the engineering structures, based on earlier developed chaos-geometric and vibration blind source monitoring approach. In the concrete realization the novel approach includes a combined group of blind source monitoring , non-linear analysis and chaos theory methods such as a correlation integral approach, average mutual information, surrogate data, false nearest neighbours algorithms, the Lyapunov's exponents and Kolmogorov entropy analysis, nonlinear prediction models etc. As illustration we present the results of the numerical investigation of a chaotic elements in dynamical parameter time series for the experimental cantilever beam (the forcing and environmental conditions are imitated by the damaged structure, the variable temperature and availability of the pink-noise force). Using numerical time series analysis results, we list the data on the topological and dynamical invariants, namely, the correlation, embedding, Kaplan-Yorke dimensions, the Lyapunov's exponents and Kolmogorov entropy etc and consider a construction of the engineering structures (including nuclear reactors) damage detection prediction model. Under an influence of the operational, environmental conditions, including the emergency incidents (accidents) during the operation of the nuclear reactor vessel it is more than probable development (growth) of damages (defects) that existed initially, as well as the emergence of new defects and their further development (growth). In this case technical application of vibration diagnostics technologies and further analysis within the presented approach could be very useful together with available probabilistic models for assessing the safety of nuclear reactors.

Keywords: damages of engineering (vibrating) structures, nuclear power plants, new mathematical models, new microsystem technology, chaos-geometric approach

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НОВИЙ КОМБІНОВАНИЙ ХАОС-ГЕОМЕТРИЧНИЙ ПІДХІД І МЕТОД МОНІТОРИНГУ BLIND SOURCE ДО АНАЛІЗУ І ДЕТЕКТУВАННЯ УШКОДЖЕНЬ ІНЖЕНЕРНИХ СТРУКТУР (ЯДЕРНІ РЕАКТОРИ) ПРИ ЗМІНІ ЕКСПЛУАТАЦІЙНИХ УМОВ, УМОВ НАВКОЛИШНЬОГО СЕРЕДОВИЩА, АВАРІЙНИХ ІНЦИДЕНТІВ

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Реферат

Стаття присвячена проблемі аналізу, ідентифікації та прогнозування наявності пошкоджень, які вище певного рівня можуть представляти серйозну загрозу для інженерних (вібраційних) структур, таких як різні технічні системи та пристрої, включаючи ядерні реактори і т.д., внаслідок зміни експлуатаційних, екологічних умов, аварійних інцидентів. Вперше ми представляємо і застосовуємо новий обчислювальний підхід до моделювання, аналізу (подальшого прогнозування) хаотичного поведінки структурно-динамічних властивостей інженерних структур на основі раніше розробленого нами хаосу-геометричного методу плюс відомий алгоритм моніторингу сліпих джерел. У конкретної реалізації новий підхід включає в себе об'єднану групу blind source моніторингу, нелінійний аналіз і методи теорії хаосу, такі як метод кореляційного інтеграла та середньої взаємної інформації, алгоритми помилкових найближчих сусідів та сурогатних даних, аналіз на основі показників Ляпунова та ентропії Колмогорова, моделі нелінійного прогнозування і т. д. в якості ілюстрації наведені результати чисельного дослідження хаотичних елементів в тимчасових рядах динамічних параметрів для експериментального консольного пучка (вплив і умови навколишнього середовища імітуються ушкодженою структурою, змінною температурою і наявністю сили типу рожевого шуму). На основі аналізу чисельних часових рядів отримані дані про топологічні і динамічні інваріанти, а саме: кореляційну розмірність, розмірності вкладення, Каплана-Йорка, показники Ляпунова, ентропію Колмогорова і т.і., і розглянута конструкція моделі прогнозування і виявлення пошкоджень інженерних споруд, у т.ч., ядерних реакторів. Під впливом експлуатаційних, екологічних умов, у тому числі надзвичайних інцидентів (аварій) під час експлуатації корпусу ядерного реактора є більш, ніж імовірним розвиток (зростання) шкодувань (дефектів), що існували спочатку, а також виникнення нових дефектів та їх подальший розвиток (зростання). У цьому випадку технічне застосування вібраційно-діагностичних технологій та подальший аналіз в рамках розвинутого в роботі підходу можуть бути дуже корисними разом із існуючими імовірнісними моделями для оцінки безпеки ядерних реакторів.

Ключові слова: пошкодження інженерних (вібраційних) споруд, атомні реактори, нові математичні моделі, нова мікросистемна технологія, хаос-геометричний підхід