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DAMAGE ANALYSIS AND DETECTION UNDER VARYING ENVIRONMENTAL AND OPERATIONAL CONDITIONS USING A CHAOS THEORY METHODS

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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 (hydrotechnical equipment, hydro-electrical station engines, atomic reactors ones etc). Usually change of structural dynamic properties due to environmental, operational and other effects allows to determine the existence, location and size of damages. We present and apply an effective computational approach to modelling, analysis of chaotic behaviour of structural dynamic properties of the engineering structures. The approach includes a combined group of 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 (environmental conditions are imitated by damaged structure, variating temperature, availability of a pink-noise force). For the first time we list the numerical data on topological and dynamical invariants, i.e., correlation, embedding, Kaplan-Yorke dimensions, Lyapunov's exponents and Kolmogorov entropy etc.

Key words: structures with damages, environmental and other effects, nonlinear analysis, chaos, methods.

Introduction

One of the important problem in monitoring the engineering (vibrating) structures (such as different mechanical and hydrotechnical systems, devices, equipment, including turbochargers, engines of hydroelectrical stations, atomic reactors etc) is problem of analysis, identification and further prediction of the presence of damages (cracks), which above a certain level may present a serious threat to their performance [1–12]. The standard way is using so called structural health monitoring (SHM) methods [1–6] 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 effects allows to detect 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 Refs [1–3].

From experimental viewpoint, especially valuable are now methods of nondestructive testing, in particular, vibro- diagnostics (see details in Refs. [3–10]) 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 etc have been discussed. Especial interest attracts the pointwise summation of similar Wavelet Transform Modulus Maxima decay lines, which has been used in [3] 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 [3] 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.

In this paper we present and apply an advanced computational approach to analysis, modelling and further prediction of the corresponding chaotic time series, which represent the structural dynamic properties of the vibrating structures. The computational code applied includes a combined set of non-linear analysis and chaos theory methods such as an autocorrelation function method, correlation integral approach, average mutual information, surrogate data, false nearest neighbours algorithms, the Lyapunov's exponents and Kolmogorov entropy analysis, spectral methods and nonlinear prediction (predicted trajectories, neural network etc) algorithms (in versions [12–50]). The results of the numerical investigation of the chaotic elements in time series for the experimental cantilever beam [3] (the forcing and environmental conditions are imitated by the damaged structure, the variable temperature and availability of the pink-noise force) are presented. Numerical data on the topological and dynamical invariants, namely, the correlation, embedding, Kaplan-Yorke dimensions, the Lyapunov's exponents and Kolmogorov entropy etc are for the first time listed. All calculations are performed with using "Geomath" and "Quantum Chaos" computational codes (see details in [51–98]).

The input data and method of a nonlinear analysis and testing for chaos in the response time series

As the initial data we use the data of the corresponding cantilever beam (excited by white and pink noise forces) time domain response series [3]. The detailed description of the experimental setup of a cantilever beam is presented in Ref. [3]. 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 $7.87 \cdot 10^{-6}$ kg/mm^3, Young modulus of $200 \cdot 10^6$ 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. Fig. 1 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 variating the temperature and availability of the pink-noise force). Obviously, one could consider a wide group of different environmental, operational and other effects. partic there possible Other situations are analyzed in Ref. [3].

The computational approach to studying the complex non-linear systems time series with elements of a chaos is presented in Refs. [11–23], so below we are limited only by the key ideas. Let us note that for the first time idea to apply the presented approach to damage detection in the engineering structure has been proposed in [11, 22]. In our case the displacement quantity is described by some scalar series:

$$s(n)=s(t_0+ n\Delta t) = s(n), \qquad (1)$$

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 8192 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 [14] 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.

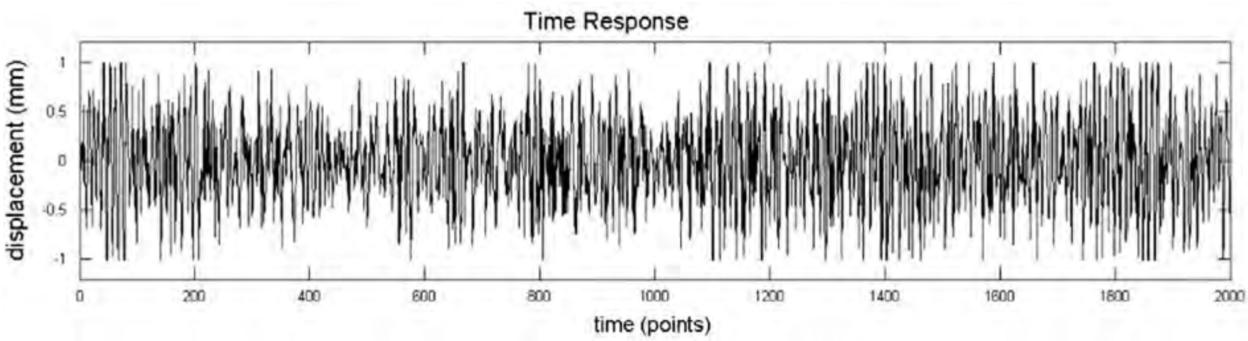

Fig. 1. The experimental cantilever beam time domain response series for the case of the damaged structure, variable temperature and availability of the pink-noise force (see text)

A set of time lags is used to create a vector in d dimensions,

$$y(n)= [s(n), s(n + \tau), s(n + 2\tau), .., s(n +(d-1)\tau)], \quad (2)$$

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 (for example, see [15]). 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 [12, 16, 17]) 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 [18] and the false nearest neighbours by Kennel et al [19].

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

$$d_L = j + \sum_{i=1}^{j} l_i / | l_{j+1} |, \quad (3)$$

where j is such that $\sum_{i=1}^{j} l_i > 0$ and $\sum_{i=1}^{j+1} l_i < 0$, and the Lyapunov exponents are taken in descending order. The details of building the possible prediction models for non-linear systems with a chaotic elements can be found in Refs. [11–13], however, below we are limited only by computing the topological and dynamical invariants for the studied system. The problem of building an adequate prediction model for the studied system will be treated in the separate paper.

The results and conclusions

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 ($I_{\min 1}$) 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 2 we list the 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}) for the studied time series (see text)

$C_L = 0$	114
$C_L = 0.1$	68
$C_L = 0.5$	6
$I_{\min 1}$	9

Table 2

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 (t) for the time series

τ	d_2	d_N
68	7.68	9 (9.1)
6	5.45	6 (1.3)
9	5.48	6 (1.3)

The Table 3 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.

Table 3

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 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 %. 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. To conclude, for the first time we have presented the computational data on the topological and dynamical invariants (the correlation, embedding, Kaplan-Yorke dimensions, the Kolmogorov entropy, computed Lyapunov's exponents etc) analyzing the experimental cantilever beam time domain response series (the forcing and environmental conditions are imitated by the damaged structure, the variable temperature and availability of the pink-noise force). It should be noted that a concrete technical realization of the methodologies supposes a comparison of the real signals and some elementary ones. Their 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. It is of a great interest to apply our approach to studying the damages, which above a certain level may present a serious threat to the engineering (vibrating) structures such as hydrotechnical systems, equipment, including turbochargers, engines of hydroelectrical stations, atomic reactors etc for different conditions [3,4,35-37]

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