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# Monitoring Technical Conditions of Engineering Structures Using the Non-Linear Approach

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**Abstract.** Conventional methods of monitoring technical condition are based on detection of damage in the structures of buildings or facilities during the entire period of their operation. In spite of considerable interest displayed to this issue and a significant number of publications, there is no unity of opinions. These methods differ from each other in the sets of values fixed for investigations, the techniques of their recording, transfer and further processing. Today's rules and regulations for structural designs expand the scope of application of the structures operating in the elastic-plastic stage. These damage-free structures originally display the non-linear properties and can be adequately described only by the non-linear models. This paper presents a method for determining the type and level of non-linearity from the structural oscillations data for monitoring the change in the health of structures. It is shown that a plot of acceleration against the magnitude of the displacement represents the restoring force of a structure. If the structure is damaged during a new striking motion, the phase trajectories in plane "acceleration-displacement" will deviate from its healthy signature.

## 1. Introduction

Expanding capacities of technological equipment, high speed rates and cargo-carrying capacities of the transport vehicles on the background of the increasing seismic activity have raised the significance of dynamic design calculations, which must ensure the maximal reliability of the systems. Either the theoretical and computational approach or the theoretical and experimental approach is generally accepted as a method of constructing dynamic models. The first approach is implemented at the stage of the structure design and consists in constructing theoretical mathematical models based on the application of the fundamental laws of the discrete and continual system mechanics which are expressed by analytical ratios. The second approach is based on the application of the methods of parametric and/or non-parametric identification. The models developed according to the results of the

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experimental data have a number of advantages due to the fact that they more adequately depict the characteristics of the dynamic behaviour of the actual structure. Even though a significant error may be present in the models based on the experimental data, the results obtained with these models are generally of satisfactory approximation.

One of the ways of increasing the reliability of construction elements and buildings is monitoring of their technical condition. The main purpose of monitoring is to predict the possibility of damage, state of emergency or to establish emergency operation of the object of research. For this purpose, in the beginning, the reaction is fixed on a permanent or temporary, and maintenance, or test actions. In the next step, application of regression techniques by numerical simulation is performed to evaluate the performance of the object.

## **2. Methods of structural health monitoring**

Conventional methods of monitoring technical condition are based on detection of damage in the structures of buildings or facilities during the entire period of their operation. In spite of considerable interest displayed to this issue and a significant number of publications, there is no unity of opinions [5 - 9, 11]. These methods differ from each other in the sets of values fixed for investigations, the techniques of their recording, transfer and further processing. However, with all their diversity, the structural health monitoring methods can be classified as based either on the frequency analysis or the time-dependent parameters [5-9, 11].

The damage identification methods, which are based on the frequency parameters and attribute the defects occurring in the structure to the deterioration of its structural stiffness, have found the wide-spread application. These methods use the finite element models for the estimation of the values of linear modal parameters, namely, the natural frequencies and the mode shapes, for the identification and, in some cases, even for location of the damage. It is assumed that the changes in the modal parameters of the structure during its life period are directly related to the occurrence of damage. These methods have been effective for the identification of substantial damages in the structures, but they are inapt in detecting the moment of the damage origination. It is worth noting that the changes in the frequency parameters and the mode shapes in the buildings and premises may be caused by the altered conditions of operation, and that restricts the application of the frequency-based method for the identification of significant damage.

The main shortcoming of all conventional methods [5-9, 11] consists in the fact that the same linear dynamic models are used in the analysis of the structure in its initial damage-free state as well as in the damaged condition, and that is contradictory with the basic principles of the physical process. The nonlinear effects in the above mentioned methods are averaged and divided evenly between the parameters of the individual modes.

The time-dependent algorithms are based on the calculation of certain parameters over a predetermined period of time. These parameters include deformations (stress), buckling in the structures, building tilts, vibration amplitudes, etc., which are evaluated and compared to the reference values prescribed in the relevant construction Standards and Norms.

## **3. Damages and defects as the sources of nonlinear dynamic models in the building structures**

Non-linearity of dynamic models in structures stems from geometrical non-linearity, the non-linear functioning of construction materials, non-linearity of dissipative forces. Today's rules and regulations for structural designs expand [12, 13] the scope of application of the structures operating in the elastic-

plastic stage. These damage-free structures originally display the non-linear properties and can be adequately described only by the non-linear models.

Cracks are one of the most common types of such damage; they can open and then close under operational loads. This type of damage includes: fatigue cracks, which occur near the bolt holes in truss joints; cracks caused by destruction of fragile structural materials; cracks resulting from significant deformation of the structure.

The response of the structures damaged with cracks to the repeated application of the operational loads is non-linear if during the recording of experimental data the cracks alternately open and close. In the contrary case, the response of the system is linear and the presence of cracks will only change the geometrical characteristics of the system. In a number of instances, it is difficult to simulate the actual dynamic behaviour as such, because any real structure has a well-defined specific pattern of crack locations.

Another common type of damage that leads to the non-linear response of the structures is the destruction of connections and fixtures. This category of defects includes not only the delaminating of the glued joints in the wooden structures but also in adhesion between concrete and reinforcement in the reinforced concrete structures or the destruction of bolt connections of the metal members. The emergence of structure-borne noise and thumps when uploading the structure with the operating loads is usually associated with a loss of bonds. The loss of bonds is one of the causes of crack development; moreover, cracking leads to the loss of bonds.

#### 4. Selection of recorded values and experimental data processing

Traditionally, monitoring technical condition of structural elements in buildings and facilities is based on the application of measuring instruments for the survey of deformations and displacement of building structures and ground. A set of recording equipment, the points of location of individual sensors and the methods of data transmission are assigned individually. According to experimental data, the basic natural frequency ranges and Eigen vibration modes are determined. The next step is to calibrate the initial finite-element model. This approach has gained widespread acceptance. There are, however, a number of significant limitations to its successful application.

In particular, synchronization of the concurrent operation of sensors as well as discretization of the signals continuously coming from the sensors has significant impacts on the accuracy of the results obtained. As it is shown in research [4], the most efficient procedure consists in transferring the continuous signal  $y_i(t)$  detected by the  $i$ -th sensor into its discrete form  $y_i(i\Delta t)$  at the discrete sampling rate of  $f = (10...20)f_{\max}$ . The maximum frequency value present in the signal  $f_{\max}$  can be determined either by filtering high frequencies in the circuit connecting the sensor to an analogue-digital converter or according to the frequency parameters of the sensor. In each of these cases the following condition should be met:

$$A(f_{\max}) < 0.05 \max(A(f)), f > 0 \quad (1)$$

where  $A(f)$  is the module of the discrete Fourier transform for the transformation process  $y_i(i\Delta t)$ . When processing the results of the tests, which were conducted for the purposes of identification, it appeared that the value 200 Hz was sufficient frequency [4]. This limitation is in full compliance with the international standards and the Directive of the Cabinet of Ministers of Ukraine [14].

Another limitation consists in the simplicity of registration of the points of acceleration in the structure; nevertheless, in certain circumstances a number of individual points are inaccessible for registration of displacements.

The basic sources of noise are both a process of treatment of time processes and process of their receipt. Work of sensors depends on their quality and from different external factors taking place in the experiment. The range of noises, occurring at treatment of time processes, is quite wide. For suppression of noises there is a range of methods of rough-down of time processes. However, in every special case, a level is estimated by a specialist in the area of artificial perception in the manned regime. Obviously, that identification of noise requires the qualification of an expert from a researcher. So, inexact estimation of parameters of noise can result in the off-grade rough-down of time processes. In most cases, there is no *a priori* information about the character of noises, therefore the parameters of the method of rough-down of time processes sneak up by tuning.

It influences further process of treatment of time processes. As it is shown in [8], the underestimation of the level of multiplicative noise causes large breaks of the contours of the objects at the solution of the task of contour segmentation. It, in same queue, influences the error of recognition of these objects. Overextension of the level of additive Gausse noise conduces to breaking out of the contours of the objects, and that also affects the error of recognition. In filtration of time processes linear, non-linear and mixed methods are selected.

The use of the special receptions is required in non-linear methods, as the application of ordinary spectral or other linear filters can result in distortion of nonlinear structure of time row. Nonlinear filtration in contrast to linear does not lean against information in the frequency area with the purpose of distinction or clearing of useful constituent of time row from noise. Instead, nonlinear filters utilize the reconstructed phase space, in which the determined small-size geometrical inclusions are searched for, subsequently clearing them from noise components. The volume of information, which can be extracted from the finite set of points of a time row, depends on the properties of phase trajectories and on the properties of the dynamic model, generating these trajectories.

However, in the tasks of reconstruction of the time row, the properties of phase trajectories are *a priori* unknown; therefore doing some preliminary estimation of their parameters is impossible. The analysis shows that even at noised time process the numerical estimation of parameters of the model becomes rather inconvenient. The given fact is a signal to remove some percent of noise from the time process. It will allow investigating the dynamics of a mechanical system, instead of the dynamics of noise and, finally, receiving authentic numerical results.

## **5. The phase trajectories in the identification of dynamic models of building structures**

Dynamic behaviour of mechanical systems is usually presented as oscillating processes in various graphic forms such as time processes, the Lissajous patterns and hodograph. Such patterns of presentation enable to determine the type of a process and to perform numerical estimations of its characteristics, but do not disclose any properties of the governing system. In contrast, classic phase trajectories have a range of advantages.

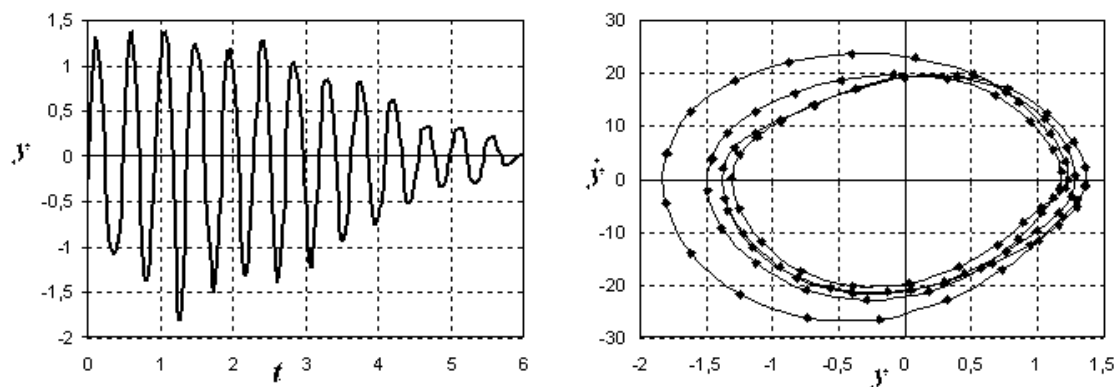
The study of the qualitative behaviour of a dynamic system implies the investigations into the behaviour of the trajectories in the phase space. The basic concepts of the theory of the qualitative study of dynamic systems were laid down by H. Poincaré. Many original fundamental contributions to the development of the qualitative research methods of dynamic systems were made by A.A. Andronov [1], E.A. Leontovich [1, 2], I.I. Gordon, A.M. Lyapunov, George Birkhoff [3]. The main objective of the classical theory of the qualitative research is to determine the dynamic properties of

the systems without getting a closed form analytical solution. To meet these requirements, the phase trajectories on the plane  $(y, \dot{y})$  are commonly used.

The image on phase plane  $(y, \dot{y})$  is a more vivid presentation because it depicts inharmonic oscillations particularly well. Each phase trajectory represents only one definite clearly defined motion. A disadvantage of phase trajectories consists in the fact that they do not provide for the immediate presentation of oscillating process in time. However, this drawback is compensated by a significant advantage. The geometric presentation of a single phase trajectory or a set of trajectories allows coming to important conclusions about the oscillation characteristics. It is, foremost, true with the oscillations, which are described with nonlinear differential equations. As it has been shown by the previous investigations, the expansion of a phase space by taking into account phase planes  $(y, \dot{y})$  and  $(\dot{y}, \ddot{y})$  substantially promotes the efficiency in analyzing dynamic system behaviour. Hereby, we pass on to a three-dimensional phase space confined with three co-ordinate axes, i.e. displacement, velocity and acceleration. An interest taken in accelerations in dynamic systems is conditioned by the fact that these accelerations are more sensitive to high-frequency components in oscillating processes.

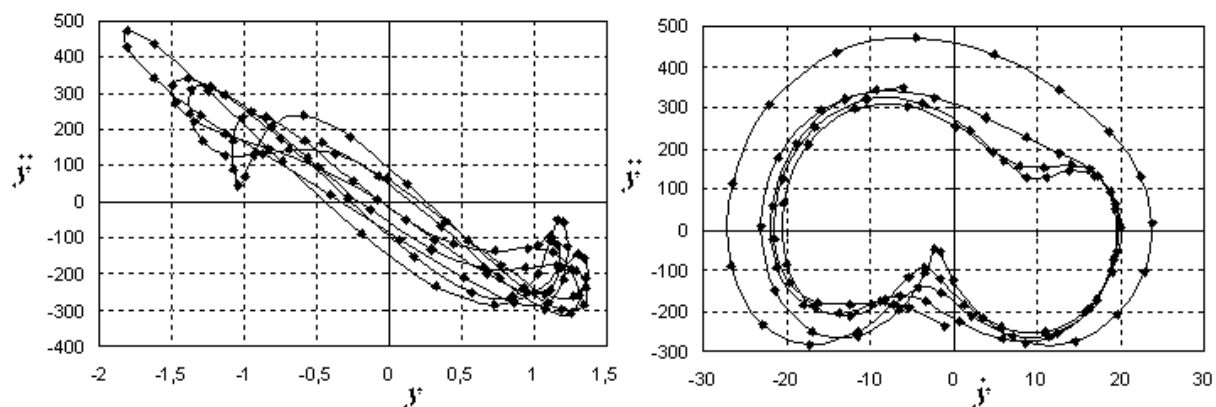
Of the main interest is the phase trajectory on the plane  $(y, \dot{y})$ . This is motivated by the fact that the energy criteria on this trajectory are interpreted most accurately. In addition, the dependence  $\ddot{y}(y)$  is antisymmetrical to the curve of elastic properties in relation to axis  $\dot{y}$ . Particularly, phase trajectories  $\dot{y}(y)$  allow for identification of the type and degree of non-linearity of the system. It is known that accelerations of points are more sensitive towards deviations from harmonic vibrations [10].

Let us perform the analysis of free damped vibrations in the reinforced concrete beam, which are presented in figure 1. The time recordings  $y(t)$  take the form of a monoharmonic process, which may represent the recordings of the displacements from a linear system as well as a non-linear system. The Poincare phase trajectories  $(y, \dot{y})$  obtained in our experiments point to the existence of one stable equilibrium state in the structure. At the same time, the phase trajectories enable to reveal the nonlinearity of the elastic characteristic and also to determine its type, e.g., a 'soft characteristic' (see figure 2).



**Figure 1.** The experimental recordings of the time processes and the Poincare phase trajectories of free damped vibrations in the reinforced concrete beam.

A peculiar feature of this system is the frequency-versus-amplitude relationship of free vibrations. Thus, in the dynamic systems with the 'soft' characteristic of elastic force, the frequency of free vibrations decreases when the amplitude increases. The identification of the given nonlinear system with the linear ones is incorrect. With the simplified linear model neither the boundaries of the zones of fundamental-frequency resonant vibrations in the structure can be defined, nor the boundaries of the zones of subharmonic and ultraharmonic vibrations, nor the boundaries of the zones of amplitude multiplicity.



**Figure 2.** The phase trajectories of vibrations in the reinforced concrete beam.

The assessment of the properties of an actual structure is realizable only with a certain degree of approximation. In this regard, one of the most important tasks in the computer-based simulation of a load-bearing structure is to construct such mathematical model that enables the introduction of those parameters and property characteristics of the structure into the model, which will substantiate the results of the field experiments.

## 6. Conclusions

Most mechanical systems show non-linear features at certain parameters of outer excitement. Various sources of non-linear behaviour that may exist in engineering structures, for example, in the structures with bolted and pin joints, reinforced structures, damaged structural elements. Non-linearity is important in many structural dynamic applications that are of interest to engineers.

The identification of a non-linear model of mechanical systems experimental data represents a distinct challenge in view of the absence of superposition principle in non-linear dynamics. The problem discussed in the paper referred to the characterization of non-linearity. The method of nonparametric identification is suggested in the paper. The method is based on the usage of the information about accelerations, displacement, and also outer excitation. It uses the methods of the qualitative theory, and also regression by methods and approximating expressions of the elastic characteristic as functions from generalized co-ordinates. The capabilities of the suggested method are limited only to noise level, measuring error and length of process. The application of the suggested method is of interest and promising for engineering application.

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