Parametric identification of multy-storey building model based on oscillation testing results

V Volkova\(^1\), L Gaile\(^2\) and L Pakrastins\(^2\)

\(^1\)Department of construction, geotechnics and geomechanics, Dnipro University of Technology, Televisiionnaya 12. ap.48, Dnipro, UA49005, Ukraine
\(^2\)Faculty of Civil Engineering, Riga Technical Riga University, 1 Kalku Street
Riga, LV-1658, Latvia

\(^1\)E-mail: drvev09@gmail.com

Abstract. Buildings and structures are complex systems having predetermined parameters, which should be controlled in the process of manufacturing structures, construction and installation. In some cases, oscillations are the most dangerous effects on the buildings and structures. Significant alternate stresses caused by oscillational actions leads to accumulation of damage in the material. It causes the appearance of fatigue cracks and destruction. In addition to fatigue failure in mechanical systems there are other phenomena that cause changes in the structure of the surface layers of the parts to be joined and consequently the reduction of the frictional force in the joint. The object of the study is a multi-storey building having a rectangular shape in plane. Structural scheme of the building is a two spans frame. The frame of the building consists of monolithic reinforced concrete structures. According to the analysis of the basic diagnostic parameters of the technical condition of buildings and structures, affect their stability and reliability are geometrical parameters of buildings and structures, and their main structural elements, as well as physical and mechanical parameters of structural elements of building and dynamic parameters of buildings and structures. An analysis of methods for determining the dynamic parameters of buildings has shown that the main criteria for assessing the technical condition of bearing structures, using the dynamic method, is the period and frequency building oscillation. Dynamic tests were conducted to determine the dynamic and rigid characteristics of bearing structural elements of the building and structures, detection of hidden defects. According to the method of measuring the dynamic parameters, the degree of damage to a building or structure, is determined by the comparison of the design values of dynamic parameters, periods of eigenoscillations, and the decrement of oscillations with experimentally obtained data.

1. Introduction
The application of methods for dynamic monitoring of buildings and structures is becoming increasingly common in engineering practice. Traditionally, according to the method of excitation of oscillations these methods are divided into the method of free oscillations, the method of seismic waves, the oscillational method of recording small oscillations - microseisms.

Dynamic structural health monitoring methods allow us to assess the state of the whole building and subsequently to localize and detect defects that can be specified by non-destructive methods. These methods can more accurately identify the risk of collapse, estimate the residual lifetime of
buildings and structures. Therefore, the development of methodology for assessing the technical condition of buildings based on dynamic criteria, which allows to increase the objectivity and reliability of the obtained results and reduce the time of the structural health monitoring is an actual scientific task. The purpose of the study is to develop a methodology for evaluating the parameters of a construction model based on dynamic criteria.

2. Relevant methods of buildings and structures identification

The issues of construction of mathematical models and prediction of dynamic behaviour of structural elements proceeding from recorded experimental data have attracted considerable interest. In spite of intensive investigations into the above mentioned matter, which have been undertaken in the scientific centers in different countries [1-4], as well as the important results obtained, there is no, so far, the only universal effective approach, which would allow for correct determination, prediction and analysis of dynamic properties in construction elements.

Most of the methods of structural identification are based on the use of special types of outer excitation for a wide range of frequencies, such as symmetric monoharmonic excitation and rectangular impulse. These types of excitation are often unrealizable in mechanical systems. The methods based on the Fourier transformation do not allow classifying and localizing non-linearity [5, 6] and are inapplicable to investigating stochastic processes [1-3, 7]. It should be also noted that the application of Wiener series and Hilbert transformation for identification of non-smooth non-linear dynamic characteristics is unjustified [2, 3].

In most of the previous analyses, damages are characterized by changes in the modal parameters, for example, natural frequencies, modal damping ratios and mode shapes. The calculating process is done using data from the structure in some initial and usually assumed undamaged condition, and then is repeated at periodic intervals or after some potentially damaging event that triggers the assessment process. Structural parameters such as stiffness matrix constructed from identified modal parameters may also be used for damage detection and localization. These methods have prevented their use in most “real-world” applications. At first, it involves fitting a linear physics-based model to the measured data from both the healthy and potentially damaged structure. Often these models do not have the fidelity to accurately represent boundary conditions and structural component connection, which are prime locations for damage accumulation. Also, this process does not take advantage of changes in the system response that are caused by non-linear effects. The values of oscillations amplitudes are small for buildings and structures. However in these cases, non-linearity of dynamic models such as a dry friction, tightening and backlash show up most evidently. There is also research using other damage-sensitive features without the need to identify the modal parameters, such as novelty analysis with auto-regressive models.

2.1. Application of trajectories in extended phase space in identification of structural elements

As it has been shown by the investigations of several authors [8, 9], the expansion of a phase space by taking into account the phase planes “acceleration – displacement” and “acceleration – speed” substantially promotes the efficiency in analyzing a 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 into accelerations in dynamic systems is conditioned by the fact that these accelerations are more sensitive to high-frequency components in oscillating processes. Phase plane “acceleration – displacement” is of particular interest in the analysis of dynamic system behaviour, because it allows a more evident interpretation of power relations in the dynamic system under investigation. Namely, the area confined by curve “acceleration – displacement” and axis “acceleration” is equal to work, and the anticlockwise motion around its contour corresponds to the energy spent by the system for one cycle of oscillating. Another important characteristic of phase trajectories on plane “acceleration – displacement” is the fact that dependence acceleration versus displacement for autonomous non-conservative systems is a mirror symmetric image in relation to axis “acceleration” to the graph of changes in elastic force characteristic.
The article [10] presents the results of experimental and analytical investigations of an essentially non-linear dynamic system. The main concept of this paper is that, if a given type of damage converts a linear system into a non-linear system, then any observed manifestations of non-linearity serve to indicate that damage is present. The author has defined behavioural peculiarities of phase trajectories and their mappings in the expanded phase space. It has performed the structural analysis of the phase trajectories obtained in the test records for oscillations of creaked reinforced concrete beam in the expanded phase space. The results of full-scale test and numerical simulation of the dynamic behaviour of the latticed sightseeing tower are presented in the article [11]. It is noted that for effective control of the structural oscillations, it is necessary to study the mechanisms of energy dissipation in real objects. The phase trajectories in the extended phase space were applied in order to identify sources of non-linearity.

3. The object of the study
The multi-storey building having a rectangular shape in plane is under studying. Structural scheme of the building is a two spans frame. The frame of the building consists of monolithic reinforced concrete structures. It is including monolithic ribbed slabs of floors and roof which connected with monolithic columns. The stability of the structure is provided by rigid disks of monolithic reinforced concrete floors and roof, as well as the rigid connections of columns with main beams of floors and roof.

According to the analysis of the basic diagnostic parameters of the technical condition of buildings and structures, affect their stability and reliability are geometrical parameters of buildings and structures, and their main structural elements, as well as physical and mechanical parameters of structural elements of building and dynamic parameters of buildings and structures. An analysis of methods for determining the dynamic parameters of buildings has shown that the main criteria for assessing the technical condition of bearing structures, using the dynamic method, is the period and frequency building oscillation.

4. Numerical modelling of building dynamic behaviour
The results were obtained with the use of the SCAD software package and implementation of Lanczos method for dynamic analysis [12]. Rectangular finite element mesh was used in research. The fundamental frequencies and modes of oscillation of the structural system were determined by solving the equation of continuous free oscillations:

\[ [M][\ddot{u}] + [K][u] = 0 \]  

where \( M \) is the mass matrix, \( K \) is the stiffness matrix, \( \ddot{u} \) is the acceleration vector, and \( u \) is the displacement vector. The finite element model of the building was formed by means of the preprocessor Forum with the import of the initial graphic information in SCAD (see figure 1).

![Figure 1. Block model of the building. Pre-processor Forum of SCAD software package.](image)

In the simulation of the rod and plate structural elements the finite elements of the type "spatial rod" and shell elements were used [13, 14]. The number of nodes in the structural scheme is 20360,
the number of elements is 28321. The number of degrees of freedom is 354960, the order of the system of linear equations is 120948. The weight of technological equipment was taken into account at implementation of modal analysis. According to the standards, it is recommended to analyze from 3 to 5 principal oscillations modes. In order to avoid the building-up of errors in integration, simulation was carried out for 10 modes of oscillation. In further investigations the first 5 modes were used. According to the results of calculations presented in Table 1 and as it seen from figures 2-5 the lower dominant forms of oscillations correspond to oscillations in the horizontal plane and torsional oscillations modes.

Table 1. Results of modal analysis.

| Mode  | Eigenvalue, Hz | Frequency, Hz | Period, s | Eigenvalue, Hz | Frequency, Hz | Period, s |
|-------|----------------|---------------|-----------|----------------|---------------|-----------|
| Mode 1| 0,083          | 1,93          | 0,518     | Mode 6         | 0,03          | 5,323     | 0,188 |
| Mode 2| 0,047          | 3,364         | 0,297     | Mode 7         | 0,023         | 6,809     | 0,147 |
| Mode 3| 0,041          | 3,883         | 0,258     | Mode 8         | 0,022         | 7,239     | 0,138 |
| Mode 4| 0,039          | 4,113         | 0,243     | Mode 9         | 0,021         | 7,417     | 0,135 |
| Mode 5| 0,034          | 4,694         | 0,213     | Mode 10        | 0,02          | 8,042     | 0,124 |

Figure 2. First oscillations mode. The translatory oscillations relative to the axis X.

Figure 3. Second oscillations mode. The translatory oscillations relative to the axis Y.

As it shown in figures 2 and 3, the nature of the deformation of the building has a pronounced translational character. Structures and its joints oscillate as one unit. It leads to a more uniform stress distribution.
Figure 4. Third oscillations mode. The torsional oscillations.

Figure 5. Forth oscillations mode. The flexural oscillations.

Investigations were performed in a passive experiment. Figure 6 shows the time process and the spectral characteristics of oscillations of building. External excitation was generated by technological equipment which alternately turned on and off. In Figure 6, we can find separate region of the existence of the buildup and modes of oscillations with large amplitudes corresponding to the inclusion of individual machines and small oscillations representing structure shimmering.

Figure 6. Time processes and spectral characteristic of the forced oscillations of building oscillations.

On the spectral characteristic (figure 6) one can notice two frequency spikes. The first of them corresponds to the first mode of the building oscillation and is equal to 1.8 Hz. The second spike reflects the frequency of external excitation created by the equipment 1 at frequency 4.8 Hz. The original record of the time process was divided into separate samples corresponding to individual
technological cycles. Figure 7 shows the time process and phase trajectories of forced oscillations of building on the phase planes \((y, \dot{y}), (y, \ddot{y}), (\dot{y}, \dddot{y})\). The process under study is not stationary due to the fact that the eigenfrequencies and the frequency of the external excitation do not coincide.

![Figure 7. Time processes and phase trajectories of building oscillations.](image)

Let us analyze the structure of phase trajectories on the plane “acceleration - displacement”. As it can be seen from figure 7 the structures of phase trajectories in the region of positive and negative displacements are different. In the area of negative values of displacements, the system exhibits properties inherent to the linear systems. So the skeleton curve looks like a straight line. This fact can be explained by the elastic stage of the concrete in compressed zone. At the same time, in the region of positive displacement values, the skeleton curve of phase trajectories on the plane “acceleration - displacement” takes the form of a parabola. This is typical for systems with a “soft” characteristic of restoring force. The cause of this phenomenon is the elastic - plastic stage of material in the stretched zone of the section.

5. Parametric identification of dynamic model

The main concept of this paper is that, if a given type of damage converts a linear system into a non-linear system, then any observed manifestations of non-linearity serve to indicate that damage is present. In its undamaged state an assumption that the structures can be modeled as a linear system is quite adequate, but consider what happens when a crack is introduced.

On the basis of results received in [10], generalization was executed and formulated recommendation to application of phase trajectories on a plane “acceleration- displacement” to assessment of parameters of dynamic models. It was assumed that dependence of restoring force can be presented cubic dependence \(R(y) = \alpha y + \beta y^3\). Thus, will get the dynamic system, described differential equation of a view

\[
y + \varepsilon \ddot{y} + H \text{sgn} \dot{y} + \alpha y + \beta y^3 = F(t).
\]  

This type of restoring dependence can be accepted for most practical applications, the therefore entered supposition does not affect community of results. The obtained phase trajectories can be considered as consisting of separate elements. The shape of phase trajectories and sizes of separate elements depend on correlation of parameters of equation (2). Shape of phase trajectories on a plane
“acceleration- displacement” (figures 8, 9) for the oscillations on fundamental tone of the mechanical non-linear systems with the combined friction, represent equation (2), determined the values of parameters $\varepsilon$, $H_1$, $\alpha$, $\beta$.

**Figure 8.** Elements of phase trajectories of the system (2) for the following values of parameters:

$a$ – $\varepsilon = 0$, $H_1 = 0$; $b$ – $\varepsilon = 0$, $\alpha = 0$, $\beta = 0$; $c$ – $H_1 = 0$, $\alpha = 0$, $\beta = 0$.

The phase trajectories on plane “acceleration- displacement” change its shapes and places for some set of parameters $\varepsilon$, $H_1$, $\alpha$, $\beta$ with dependence of frequency of outer excitement. For some set of parameters $\varepsilon$, $H_1$, $\alpha$, $\beta$, phase trajectories will change its shape and position on a plane “acceleration- displacement” depending on frequency of outer excitement. At the increase of frequency of outer excitement length of phase trajectories will be increased, arriving at a maximum value at resonance, and quickly to diminish after passing of resonance frequency.

**Figure 9.** Phase trajectories of fundamental tone oscillations the combined friction and non-linear restoring dependence: $a$-the systems with “hard” restoring dependence; $b$ – with “soft” restoring dependence.

The phase trajectories of resonance oscillations in the frequency of external excitement is important for determination of parameters of restoring force. Having regard to the features of dynamic behaviour of the systems with non-linear restoring force for control of accuracy of parameter estimation. It is expedient to use a few phase trajectories on a plane “acceleration-displacement” corresponding to a few frequencies of outer excitement. Assessment of values of parameters $\alpha$, $\beta$ can be executed either by the appeal of the known analytical solutions or by interpolation. For example, it will suppose that amplitudes $A_1$, $A_2$ and frequencies $\omega_1$, $\omega_2$ of oscillations of fundamental tone, proper the close to resonance regime are known. With the purpose of determination of parameters $\alpha$ and $\alpha$ we will take advantage of the known averaging solution for finding of frequencies of resonance oscillations $\omega^2 = \alpha + 0.75 \beta A^2$. Then, for two successive values of frequencies will receive the system of two equations. By solving it we have:

$$\alpha = \left(\omega_2^2 - \omega_1^2\right) / \left(A_1^2 - A_2^2\right)$$

and

$$\beta = 4\left(\omega_1^2 - \omega_2^2\right) / 3\left(A_1^2 - A_2^2\right).$$
Analysing a figure 9, it is possible to note that the value of the module of dry friction $H_1$ can be measured directly at treatment of phase trajectory in a point $y = A_1$, and the value of coefficient of viscous friction can be defined from correlation $G_{ij} = 2 \pi \omega \varepsilon A + H_1$, where $G_{ij}$ is distance between intersections by a phase trajectory with $ax = \dot{y}$. Exactness of the estimated values of parameters of viscous and dry friction can be appraised the lead through of alternative calculations on the known formulas.

6. Conclusions
The identification procedures were applied to treatment and analysis of the results from the full-scale dynamic testing of the building. Appropriate time traces of free oscillations from the experimental records were selected for application of the method. The extended phase space is built from the general aggregate, its phase trajectories and their mappings.

Phase trajectories on an acceleration-displacement plane allowed to attribute the investigated system to the family of the asymmetrical systems with an asymmetric, non-linear dependence of restoring force. The non-linear character of restoring force of flat was depicted presence of defects and damages of reinforced concrete structure. In particular, at the oscillations of crack of structures alternately opened and closed, that causes change in flexibility. Another factor explaining asymmetry of restoring dependence is a presence of one-sided connections between plate and beams.

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