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Taking Account of Nonlinear Properties of Subsystems in Problems of Dynamic Interaction of Structures with Loads, Bases and Flows

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Abstract
This paper describes the additional features of discrete models of various DOF systems to solve nonlinear dynamical problems of complex-compound buildings and structures including elements of significant flexibility (bridges, pylons and supports of power transmission lines, pipe line crossings, guyed masts etc.). Qualitative and quantitative differences between linear solutions (which are popular among FEM designers) and nonlinear solutions (depending on geometrical, physical and constructive nonlinearities) are discussed It is analyzed the time-history models of different combinations of mention structures with the adjacent subsystems, damping devices (well-known and the most-recently-used), static and dynamic loads and effects (including moving loads).

There is also presented experimental and theoretical approach of damages determination for rod elements in the spatial structure by the dynamic diagnosis method (e.g. for bridges crane with the big span).

Keywords
Nonlinear structural dynamics; modelling; geometrical, physical and constructive nonlinearities; damping; tuned mass damper; diagnosis of damage.

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Introduction

At present there are many manuals and textbooks on dynamics and stability of different structures. Among them scientific researches and developments on nonlinear dynamics of structures are not numerous. We can mention, as example, publications [1, 2]. In scientific researches relating to long span and flexible structures [3-6] some specific approaches to solve problems of the structures nonlinear dynamics are proposed. There are also recent publications on vibrations of discrete and continual nonlinear systems with dampers [7], on vibration protection [8] etc. In engineering modeling of different constructions and structures and its damping arrangements working under seismic and other loads [9] different approaches to account dynamic properties and design of the constructions and structures are used [10, 11].

Modern civil engineering tendencies make engineers and developers in specialized software systems to devote more time and forces to dynamic problems. It causes the clampdown. For example, in Ukrainian National Construction Regulation (National Building Code) on civil engineering in earthquake generating region [9] there are planning condition specifications of some structures by direct dynamical method of synthesized accelerograms' input and then this problem is solving in temporary area. On the other hand, original software systems don't yet allow modern designer to simulate the dynamics of complicated building and structures in temporary area if they include constructions, multiple bar joints, braces, environments, damper devices and other subsystems with nonlinear properties and characteristics.

In addition, in dynamic models of unique construction projects it would be correctly to raise immediately the question of taking into account several-sorted basic nonlinearities for this construction project. Practice of holding in-place and laboratory tests and calculations by researches shows that in analysis of free and forced structure vibrations it is advisable to make the following:

- to determine nonlinear characteristics of subsystems out from the purposeful experimental investigations under dynamic and statistic loads;
- to classify the given nonlinear characteristics for certain multiple types of buildings, structures, multiple bar joints, braces and other subsystems according to most important groups, namely: geometrical, structural and genetic ones;
- to develop efficient software programs (bundled software integrated into BIM-technologies) of civil engineering field to install input of any component packs in the model and reactions' investigations of different nonlinear building and structure models in temporary area (acceleration control, displacements, dynamic loading stresses etc.):
- to encourage the engineering manuals and development of more specific search solving methods of possible solving ways of the complicated practice nonlinear dynamic tasks (comfort and safety) for construction projects assisted by scientists, civil engineers and bundled software.

Some specific tasks on nonlinear dynamics of structures are considered in the following paragraphs.

1. Introduction of geometrical nonlinearities in the case of construction projects with slender elements (threads)

In modern complicated structures efficient long-span constructions with slender elements (hanging threads, back-guys, guy cables, anchor stays) are often used. Let us start with two key questions of lateral-force design for such structures, namely, the account of the slender elements (i.1) geometrical nonlinearity and constructive friction in multiple bar joints (i.2).

Peculiarities of own model composition (for slender elements) are considered in details in [2]. Foregoing models allow to perform a simultaneous analysis both static and dynamic work of slender elements taking into account the geometrical nonlinearity so that sets apart them from the traditional approaches (cited, an example, in works by Kachurin V.K., Ivovich V.A., Kirsanov N.M., Shimanovskiy V.N. , Ogloblya A.I., etc).

In terms of test calculations the hanging filament with 30 meters long span was taken as an example: the original boom with 1.5 meters slack (i.e. $f_0 / l = 1/20$). The cross-section of steel round weldless tube with overall opening diameter 76.2x3mm, load-ultimate dead with length of a thread 5.5 kg/m (only proper pipe weight that allows to set down the system as a thread with finite rigidity). Dynamic model is presented as a plane grid of 16 links, 15 concentrated mass (30 dynamical degrees of freedom). The testing was held according to the analytical data value of other authors as well as FEM (deflections, bending moments, three lowest frequencies). Procedure deviations for constructions with the socketed pier are less than 5%, but for rigidly restrained supports - 7%.

It is well-known that the proper frequencies of hanging filaments (slender elements) depends on vibration amplitude. The skeletons for some nonlinear systems may be characterized by complex functions. Fig.1 shows the skeletal curves of the lowest forms for described above construction.

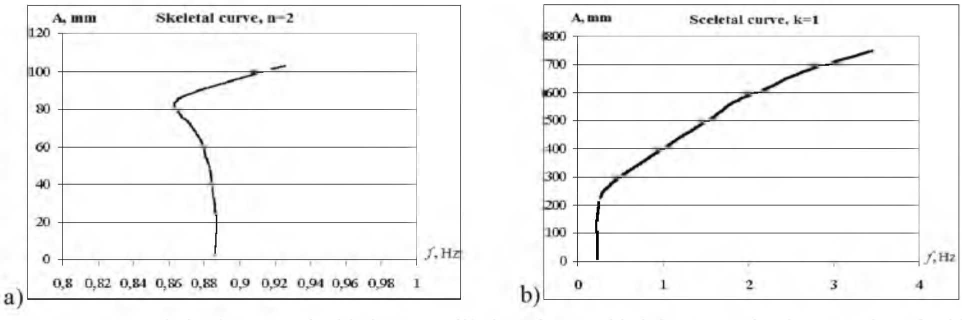


Figure 1. Skeletal curves of cable lower oscillations forms with $f_0/l=1/20$: a) in plane sagging of cable; b) from the plane of sagging of cable

Fig.1,a shows the character of skeletal curve type, between "soft" and "rigid". Starting from the very small amplitude (of order at $0.03f_0$) the suspended structure vibrations are determined obviously by nonlinear character that must be taken of calculations. In Fig.2 the diagram scanning application of dynamic load frequency and vibration records of amplitude changes for vertical and horizontal displacements of midsection of pipe line suspended structure are presented.

As is obvious, the amplitudes of section vibration are asymmetric in terms of equipoise which indicates evident nonuniform rigidity due to vertical forces. The amplitudes' formula of vertical vibrations (on each side of equilibrium limit of system) equals about 7.

It is important to note that the vibration records obtained in terms of friction that equals 7% of critical. This formula is considerably reduced with friction increase to 15% of critical – to 1.4, but in terms of friction that equals 45-50% of critical the formula verges towards symmetry indicator.

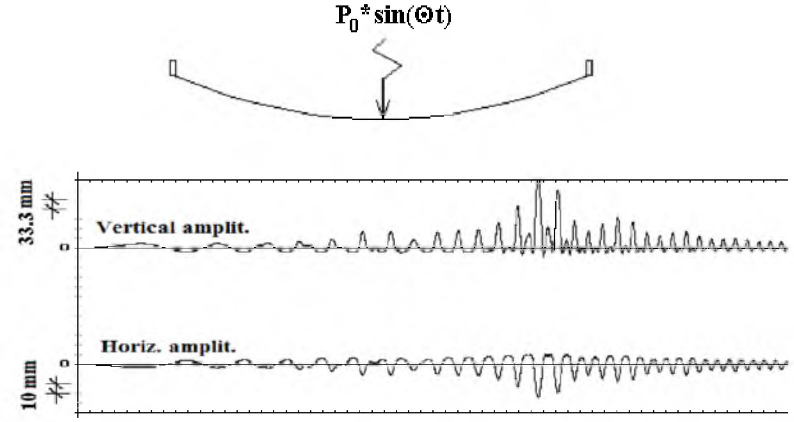


Figure 2. Vibration records of forced vibrations of geometrical nonlinear dynamic model for suspended structure

2. Introduction of constructive-physical nonlinearities as illustrated by friction in multiple bar joints of suspended structures

The suspended constructive elements in complicated structures, as a rule, cause the movement (and deformations) of neighboring structures (pylons, pillars, column, etc.), subsystems (e.g. devices, machines and mechanisms) and environments (air environment with flows and sediments such as snow, ice-covered ground; earth foundation). To know a durability of the slender elements the static and dynamic analysis must be made. Also, structures with suspended and other elements nods and steel structure joints with high-strength boltings are often used. In this case the dry friction forces occur between connection surfaces. So, to considerate the cooperation in terms of dynamic loads it is very important to take into account not only elastic, but dissipative nonlinear component too. To estimate adequate models for simulation, the suspended elements may be presented as computational scheme elements interacting with neighboring structures. These structures are presented as nominal equivalent elastic-dissipative balks which model elastic and non-elastic parameters of these structures in flexible heel joint. Besides, the installation of elastic dissipative balks in supporting nodes also allows to solve the vibro-insulation problems in neighboring structures (either own flexible elements).

Fig.3 shows a fragment of model of some suspended element with installation of elastic-dissipative balks in heel joints.

In the representation of computational schemes working cooperatively with the neighboring structures, are considered either the elastic or non-elastic characteristics or parameters. In Fig.4 the fragment of similar structure model is shown (e.g., head pylon node of suspended bridge with the flexible main cable and guys).

The friction between adjoining pylon's surfaces and cable is simulated using the element with Coulomb's friction. At that the pressing force of cable surface is defined as a sum of two components: N_1 is the compression force in a bolted assembly and N_2 is a sum of vertical projections of linear and lateral forces (variable value) in suspended thread and back stay (or in another elements suited for the pylon).The horizontal cable movements towards the pylon's guiding line are only foreseen in this model.

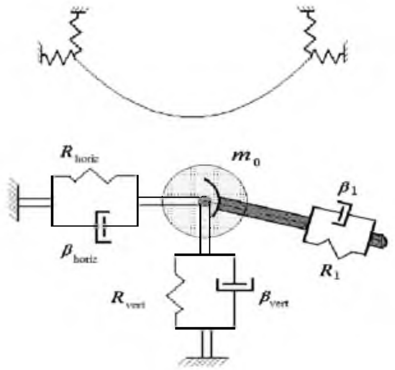


Figure 3. Scheme of heel joints of suspended structure with elastic- dissipative balks (with a viscous friction)

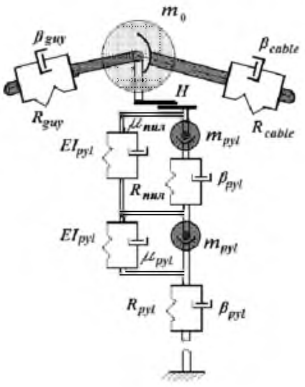


Figure 4. Fragment of dynamic node model of bearing suspended element's migration through the pylon (with the account nonlinear dry friction forces between adjoining surfaces

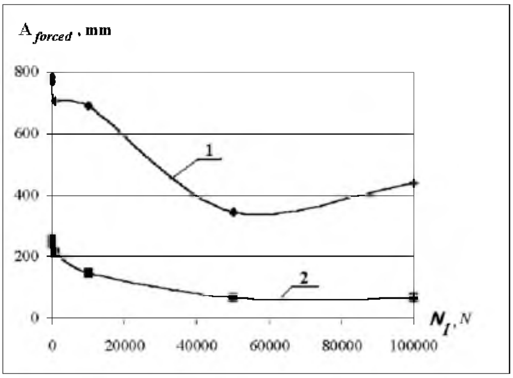


Figure 5. Dependency graphs of vertical movements of spanned structure (1) and horizontal points displacement above the supports (2) from pressing force N_1

Let us start with constrained vibrations of structures in terms of vertical dynamic mono-harmonic force of constant amplitude and frequency. The presence of Coulomb's friction in the construction model allows making a forecast such effect of nonlinear vibrations as a motion stop. As the additional pressing force is increased, the vertical and horizontal movement amplitudes are changed no uniquely. In Fig.5 are presented the dependency graphs of these values on N1 force. From these graphs we can see as an additional pressing from 0 to 104 N is under the force increasing of N_1, amplitudes of horizontal movements (Fig.2) are decreased. Besides, as N_1 =50000-100000 N the amplitude of horizontal movements equals to 65-64mm (as the dead-load stress movement is 63mm), i.e. in terms of marked friction the mass above the stay takes a practically fixed (dead) position and vibrations of spanned construction are similar to the suspended thread vibrations with rocker- fixed bearings.

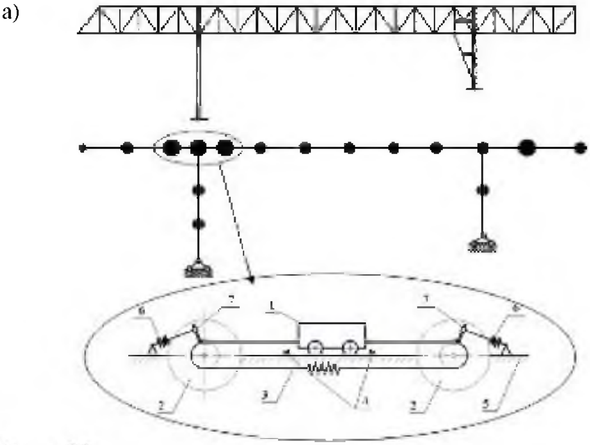
From the graph 1 of Fig.5 it is shown the authors' technics of constructional and physical nonlinearities allows to define the reasonable pressing in bolted assemblies from the perspective of amplitude decrease of geometrically nonlinear threads.

3. Examples of nonlinearity and damping vibrations of building projects

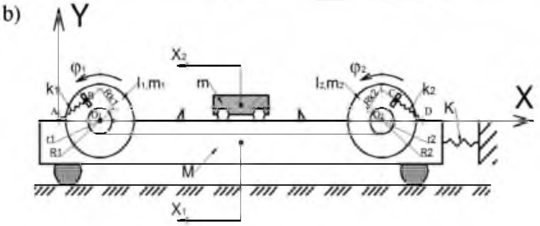
Fig.6 shows the bridge loader-crane with the bearing steel trusses. The length of such cranes is often above 140m but its' height is of 25m. To decrease the vibration and "fatigue" problems for operating, equipment and bearing structures within the high-speed traverse of vehicle with the load (approximately gross weight is 150t) different types of vibration suppressing devices are used. There are known some trigger-hydraulic devices, namely: devices which use friction when the vehicle and rail are moving; devices of damping of suspension block; TMD (tuned mass damper) etc. In the ship-to-shore cranes of foreign companies (Konecranes, Kocks Krane, Liebherr etc) the electronic and mechanic vibration damping system are used.

It is known that in TMD oriented to the vibration decrease, the main parameters of damper are its partial frequency and damping. The mass of damper is the key factor determining the damper's dimensions; it makes the translation and rotational motion.

If the elastic plastic fixturing of TMD in terms of translation motions and section with TMD of crane bridge are used, the own TMD (at the same time) may be used only for the translation motion of damper. In this case it is very convenient to set the friction-nonlinear damping of TMD mass at it's sliding along the transverse constructions and easy-to-remove plating in the upper zone of bridge section. But elastic plating are fixed, for example, above the upper main truss boom and carry the horizontal stress of inertial TMD force.



1 - weight of TMD;
2 - spools;
3 - the flexible terms (flexible body transmission);
4 - limiters;
5 - the object of vibration damping (crane-loader);
6 - elastic elements;
7 – clips



M is the mass of model of crane-loader (effective mass for the first mode);
K is the stiffness of model of crane-loader;
m is a mass of TMD's model;
k1, k2 are stiffneses of resilient terms of TMD;
$R_{1,2}$ is the biggest radius of spools;
$r_{1,2}$ is the smaller radius of spools;
$R_{k1,\ k2}$ is the distance from the spools axis to holdfasts of elastic elements of TMD;
$L0_{k1,\ k2}$ are length of the elastic terms in the initial undeformed state;
$m_{1,2}$ are the spools weight;
$I_{1,2}$ are the mass moment of inertia of spools.

Figure 6. TMD's scheme to reduce the longitudinal horizontal oscillations of crane-loader (a) and dynamic model of the crane-loader (mass M) with TMD (mass m) for damping vibrations on the test mode, arising from the movements of the trolley (b)

In the context of research of dynamic problems a patent by authors [11] develops another TMD with transformation of translation motions into rotational motions for the vibration damping of loader-crane with linear – horizontal forms of own vibrations. The structure of this damper (see Fig. 6) allows to adjust it using the displacement of compressor bars 7, choosing the initial position of contact wheel – pulleys 2, changing the mass of a body, inertia moments of contact wheel – pulley mass 2, wheel rate 6 and slender element 3 (Fig.6,a). Such TMD offers the nonlinear characteristics and allows to obtain correct ranges of the damper depending on type and effect activity.

The dynamic model of the loader-crane with TMD. If we consider only the first (lowest) form of longitudinal horizontal oscillation loader-crane in its vertical plane, the system can be approximately modeled as a system with one degree of freedom. Joining TMD under certain assumptions (transfer 3 - non-extensible, no-slip transmission 3 with respect to spool 2) adds in another degree of freedom (Figure 6, b). Here, the angular coordinates φ1 and φ2 are expressed through the generalized coordinate mass movements of TMD X2: φ1 = X2 / r1; φ2 = X2 / r2. This article discusses the option of small amplitude oscillations of TMD weight not exceeding the distance to stops 4 (Fig. 6, a).

Table 1. Auxiliary symbols and expressions relating to TMD model

original coordinates	**next coordinates**	
X_A	$X'_A = X_A - X_1$	horizontal coordinate of point A
Y_A	$Y'_A = Y_A$	vertical coordinate of point A
X_{O1}	$X'_{O1} = X_{O1} - X_1$	horizontal coordinate of point O1
Y_{O1}	$Y'_{O1} = Y_{O1}$	vertical coordinate of point O1
X_{O2}	$X'_{O2} = X_{O2} - X_1$	horizontal coordinate of point O2
Y_{O2}	$Y'_{O2} = Y_{O2}$	vertical coordinate of point O2
X_D	$X'_D = X_D - X_1$	horizontal coordinate of point D
Y_D	$Y'_D = Y_D$	vertical coordinate of point D
$X_B = X_{O1} - R_{k1} \cdot \sin(\varphi_{B0})$	$X'_B = X'_{01} - R_{k1} \cdot \sin\left(\frac{X_2 - X_1}{r_1} + \varphi_{B0}\right)$	horizontal coordinate of point B
$Y_B = R_{k1} \cdot \cos(\varphi_{B0})$	$Y'_B = R_{k1} \cdot \cos\left(\frac{X_2 - X_1}{r_1} + \varphi_{B0}\right)$	vertical coordinate of point B
φ_{B0}	initial deviation from the vertical axis BO$_1$, rad	
$X_C = X_{O2} - R_{k2} \cdot \sin(\varphi_{C0})$	$X'_C = X'_{02} + R_{k2} \cdot \sin\left(\frac{X_2 - X_1}{r_2} + \varphi_{C0}\right)$	horizontal coordinate of point C
$Y_C = R_{k2} \cdot \cos(\varphi_{C0})$	$Y'_C = R_{k2} \cdot \cos\left(\frac{X_2 - X_1}{r_2} + \varphi_{C0}\right)$	vertical coordinate of point C
φ_{C0}	initial deviation from the vertical axis CO$_2$, rad	

We obtain the following system of equations of motion for the case of free damped oscillations model:

$$\begin{cases} \dfrac{d}{dt}\left(\dfrac{\partial T}{\partial X_1}\right) + \dfrac{\partial D}{\partial \dot{X}_1} + \dfrac{\partial \Pi}{\partial X_1} = 0 \\ \dfrac{d}{dt}\left(\dfrac{\partial T}{\partial X_2}\right) + \dfrac{\partial D}{\partial \dot{X}_2} + \dfrac{\partial \Pi}{\partial X_2} = 0 \end{cases} \tag{1}$$

Dynamic motions of the system are described in terms of generalized coordinates of the linear movement of the mass loader crane and TMD, X_1 and X_2, respectively. Kinetic energy equation is:

$$T = \frac{(M + m_1 + m_2 + m) \cdot \dot{X}_1^2}{2} + \frac{m \cdot \dot{X}_2^2}{2} + \frac{I_1 \cdot \dot{X}_2^2}{2 \cdot r_1^2} + \frac{I_2 \cdot \dot{X}_2^2}{2 \cdot r_2^2} \tag{2}$$

The equation of potential energy (Δ1 and Δ2 are deformations of the elastic terms k1 and k2) is the following:

$$\Pi = \frac{K \cdot X_1^2}{2} + \frac{k_1 \cdot \Delta_1^2}{2} + \frac{k_2 \cdot \Delta_2^2}{2} \tag{3}$$

$$\Delta_1 = \sqrt{(X_B - X_A)^2 + (Y_B - Y_A)^2} - \sqrt{(X_B^{/} - X_A^{/})^2 + (Y_B^{/} - Y_A^{/})^2} \qquad (4)$$

$$\Delta_2 = \sqrt{(X_C - X_D)^2 + (Y_C - Y_D)^2} - \sqrt{(X_C^{/} - X_D^{/})^2 + (Y_C^{/} - Y_D^{/})^2} \qquad (5)$$

To account for the inelastic resistance forces (viscous friction) in the Lagrange equations are added terms, responsible for energy dissipation ($\dot{\Delta}_1$ *and* $\dot{\Delta}_2$ are speeds of the TMD elastic elements deformation):

$$D = \frac{\beta \cdot \dot{X}_1^{2}}{2} + \frac{\beta_1 \cdot \dot{\Delta}_1^{2}}{2} + \frac{\beta_2 \cdot \dot{\Delta}_2^{2}}{2}, \qquad (6)$$

where β is the damping constant of model of crane-loader and $\beta_{1,2}$ are the damping constant of TMD`s springs.

Characteristic conversion and numerical solution of the equation (1) have been carried out in the mathematical package Mathcad 14.

For a given system of TMD by Fig.6, with large displacements are possible transitions of its mass from the initial position to the next position of equilibrium. The simulation system with specific parameters of the model of bridge and TMD revealed the following:

- at small displacement frequency of free oscillations of TMD immaterial changes (0,7-0,712 Hz) during the vibration process;
- logarithmic decrement of oscillations of the system during the vibration process varies essentially (0,013-0,28);
- for large initial displacements from equilibrium of the TMD mass a process of the mass return to the initial state is non-periodic;
- for large displacement of the TMD mass a change of the equilibrium position of the mass (bifurcation) and as a result, a decrease of the TMD natural frequency up to 0.2 Hz is possible.

4. Cause of genetic nonlinearities; use of dynamic diagnostics of structures and BIM-technologies for accelerated search of damages, rating and monitoring (by a big span loader-crane)

The certification and impact analysis of dynamic diagnostics of structures in operation may be effective in the advanced search for some dangerous damage place of stress-bearing structural term. It cuts the surveying time of such huge structures, and, respectively, a breakdown time of shops and enterprises. Besides, such thin instrumentality of dynamic diagnostics can clarify some unfixed moments of “equipment history”, loading, fires, corrosion etc. and various over project surcharge of stress-bearing structural members.

Such effects of whole life history cycle of structures cause the very same problematic group of genetic nonlinearities accumulated in the form of different defects and damages changing the design characteristics. Unfortunately, till the advent of BIM-technologies, these changes aren’t still taken into account in practice, in reconstruction, in the terms of limitation objectives of service life etc. In this part it needs to list the scientific understudied combination problems of loads and actions for buildings and structures, a lot of aerodynamic problems: aeroelastic instability and windy structural safety [3], terms’ indeterminacy of different nonlinear interactions of construction works with the earth foundation and neighboring structures etc.

An experience of investigations, tests and simulation of hereunder loader-cranes at present allows to apply the dynamic diagnostics and certification methods for such large systems. This controls indirectly the technical state of bearing steel constructions of crane, and prevents the failures.

The graphic part of dynamic certificate is presented for the loading crane of piped beam construction (based on carried out experiment) in the terms of frequency spectrum of basic forms of characteristic vibrations. Based on the theoretical calculations and carried out dynamic tests of steel constructions of loading crane was prepared the dynamic certificate; its diagram is shown in Fig.7.

The shaded portions are in accordance with the basic forms of characteristic vibrations, where the frequency- variable is changing in accordance with the place, speed and mass of vehicle moving on the crane bridge. The theoretical certificate allows understanding what own modes of vibrations with the frequencies will be evident while operating at crane. The experimental certificate will make possible to monitor the technical performance of its steel constructions.

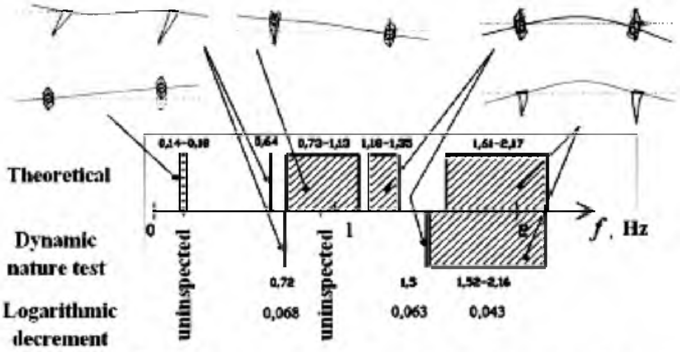


Figure 7. Dynamic passport of crane-loader tube type (graphic part)

Conclusions

In this paper, based on the series of examples dealing with the construction practice an influence of various nonlinear characteristics of these constructions and subsystems on their dynamic behavior is considered. It is proved a necessity of accounting of these properties in simulation of their dynamics. Reasonability of standardization and normalization of experimentally obtained nonlinear characteristics of structures is pointed out. Ways to increase of dynamic safety of buildings and structures are shown. These ways include use of different nonlinear characteristics during design process with subsequent refinement of the models (including movable loads case). Also wider implementation of dynamic diagnostics and BIM-technologies during phases of design and exploitation of objects is proposed.

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