Dynamic Analysis of a Chair Ropeway Exposed to Random Wind Loads

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A model of Finite Elements for analyzing the dynamic reaction of a fixed chair bicable ropeway exposed to lateral random wind loads is created in this work. Cited numerical data is for a ropeway near the town of Sliven, Bulgaria. Special attention is paid to the problem of regarding or neglecting the damping. The kinematical characteristics of the motion of the modeled nonlinear transport system are obtained.

Keywords: *chair ropeway, wind loads, dynamic reaction.*

1. INTRODUCTION

The ropeways are widely spread in mountain resorts, not only because they are convenient and fast transportation for the maintenance of ski runs, but because they are economic and ecological transportation to hard-to-reach places. Chair ropeways are preferred in regions with summer and winter mountain resorts. They are most convenient for skiers, who can travel without taking their skis off or for tourists, who can thoroughly enjoy the summer landscape. The speed at the station is slow, but between the stations it increases [9, 12]. In the chair ropeways with two ropes and fixed chairs (like the modeled one), the chairs are fixed to the pulling rope.

The question of the motion of the chairs under the lateral wind influence is of great importance. It strongly affects the comfort of the passengers as well as the safety engineering criteria during the initial calculation and later on during the periodical checks of the transport system.

It is hard to predict this type of motion theoretically and so there are few theoretic publications discussing this dynamic problem. A measuring system description for the characterization of the crosswind stability of ropeways and the measured results is described in [5], [6] and [7]. The tensile forces and stresses in the ropes caused by static loads are described in Czitary's book [4], but the dynamic background of the problem is not included. An analysis of the static behaviour of ropeways is developed, assuming a full nonlinear structural model in [3].

An analysis of the dynamic behaviour and reduction of the swinging angle of a gondola induced by random lateral wind load is done in [8]. A few years later Shioneri, etc. [11] also described the dynamic characteristics of a ropeway transport system in one tower span caused by lateral wind. Mathematical simulation of the behaviour during normal operation, free vibration and when the system is halted is presented in [2]. The authors of [2, 3, 8, 11] use Finite Elements for modeling the transport systems. In [2, 8, 11] the mathematical results are compared to experimental data and satisfactory coincidence is observed.

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2. BACKGROUND OF THE PROBLEM

As can be seen, the problem of theoretical modeling of the motion of a ropeway transport system excited by random lateral wind is of primary importance. Some of the authors [2, 3, 8, 11] prefer to use Finite Element Method, because of the complexity of the problem. This method is suitable for modeling complex multi-body elastic systems [1]. Thus the created model is closer to the real one and different material properties and geometrical constants can be regarded.

Because of the great variety of ropeways and the complex theoretical background of the problem of dynamic analysis of ropeway transport system the created mathematical models are done for already built and functioning ropeways [2, 8, 11].

Figure 1. Photo of the lower station of the double-seated chair ropeway "Sliven – Karandila"

The author of the paper, models the fixed chair bicable ropeway "Sliven - Karandila" near the town of Sliven, Bulgaria (fig. 1). This ropeway was calculated by Doppelmayr company [12] during the 1970-s. The distance between the upper and the lower stations of the ropeway is approximately 1860 m, and the displacement in vertical direction between the two stations is approximately 560 m. Its capacity is 400 persons per hour in one direction. This chair ropeway has two ropes

– one carrying rope and one pulling rope. The rollers, which support the carrying rope, are installed on 22 columns. Chairs are double seated, fixed to the pulling rope and the passengers get in and out of them at the stations, while the ropeway is moving. The leading electric motor is located in the upper station. The length of the pulling rope is regulated by a mechanism situated in a moving frame. The tensile forces are created by weight and counterweight. The passengers get in and out of the ropeway from special platforms. The working speed of the ropeway between the stations is 1.6 m/s.

3. DESCRIPTION OF THE MODEL

3.1 Finite Element Model

The problem of theoretical modeling of the motion of a ropeway excited by random lateral wind is solved using Finite Element Method. The author creates a mathematical model of a one column span of a stopped chair ropeway with one carrying and one pulling rope and fixed chairs exposed to lateral random wind loads. It is accepted that the forces and the motion of the chairs in the neighboring column spans do not influence the motion and the dynamic reaction of the analyzed span.

The model is created using standard software for Finite Elements: ANSYS, release 8.0 [1].

In fig. 2 is shown a scheme of the Finite Element model.

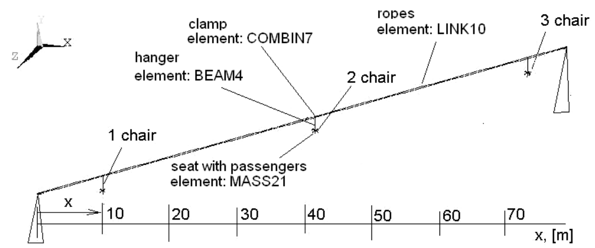

Figure 2. Scheme of the Finite Element model.

The ropes are modeled using spar elements of type LINK10. These elements are recommended for modeling sagging cables. They are preferred in dynamic analyses when inertia or damping effects have to be regarded and the motion of the slack elements is not of primary interest. These spar elements have the unique feature of a bilinear stiffness matrix resulting in a uniaxial tension-only (or compression-only) element. With the "tension-only" option, the stiffness is removed if the element goes into compression (simulating a slack cable or slack chain condition). So this option is chosen. LINK10 is a nonlinear element and requires an iterative solution. The cross-sectional area, the initial strain and some material properties such as the elastic module, Poisson's ratio and density are the necessary initial data. The initial strain effects in both ropes are also regarded. A different parametric set is input for each rope.

The chairs, including the passengers sitting in them, are modeled by concentrated masses, i.e. elements of type: structural mass MASS21. These are point elements having up to 6 DOFs. In this case the rotations about the nodal x, y and z axes are equal to zero and DOFs are reduced to 3 translations in nodal *x, y* and *z* direction for each chair. The applying point of the element coincides with the accepted mass center of the chair with passengers. Due to this, it can be out of the global vertical plane *xy* (in which both ropes lay, fig. 2)

Connections between the carrying and pulling ropes, as parts of the chairs, and seat hangers are modeled using elastic beam elements BEAM4. These elements possess tension, compression, torsion and bending capabilities. Each element is defined by two nodes, cross-sectional area, two area moments of inertia (IZZ and IYY), two thicknesses (TKY and TKZ) and material properties. The tensile, bending and the torsion stiffness equal enormous values and because of that these elements can be treated as undeformable ones. Thus the distance between the two ropes is fixed and the chair itself is treated as a rigid body, which can rotate at the pulling rope.

The clamp between the pulling rope and the chair is modeled by a revolute joint element COMBIN7. The most important capability of this element for the model is joint flexibility. In addition, its capability includes some control features. The element is intended for use in kinetodynamic analysis. It is defined in the space by five nodes: two of them are the active nodes (the coinciding nodes of the two connected bodies), a node to define the initial revolute axis and two control nodes, which are optional. The forward and the reverse rotation limits are input. The input parametric set for this element requires three translational stiffness values and two rotational stiffness values. To simulate the desired effect, great values are input. Only the torsional stiffness has smaller value, thus the rotation about the global axis *x* is modeled.

In fig. 3 is shown a scheme of the modeled span. The undeformed shape is when there are neither dead loads, nor lateral wind loads acting at the ropeway. The deformed shape is obtained when both types of loads act at the transport system

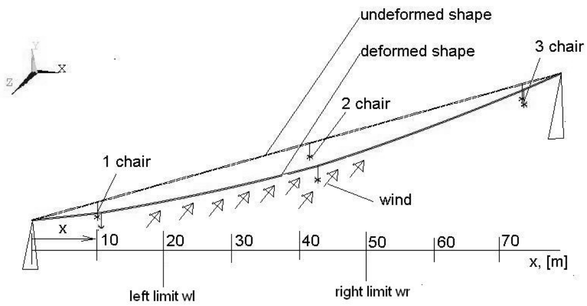

Figure 3. Deformed and undeformed shapes of the ropeway

3.2 Lateral Wind Loads

The ropeway is exposed to random lateral wind loads in a fixed section of the modeled column space. The left limit of the loaded section is marked with ***wl*** and the right limit - with ***wr*** (fig. 3). Their values are parameters marked with the same symbols and can easily be changed. This makes the developed model user-friendly. Varying of the values of ***wl*** and ***wr*** during the analyzed period of time is also possible, i.e. the position of the exposed to lateral wind loads section at the start of the simulation can differ from the position at the end of the simulation.

The function of the wind also varies in time. The lateral wind forces depend on both parameters: time and position - $W = W(t, x)$.

The most convenient way of introducing this random function is in a table, i.e. for each time interval are input the values of the wind forces and coordinates of their acting points. It is not necessary for the function of the wind forces in time to be presented by a mathematical function, as it is recommended in [10]. Data for wind function can be taken from measurements of the wind velocity in the region of the ropeway.

The method of introducing wind loads into a table is more laborious but allows the use of experimental data and later adjustments.

All wind loads in the presented numerical simulation are proportional to the square of the wind velocity, which varies in time, and to other coefficients (air drag coefficient, area exposed to the wind gust, density of the air), which remain constant during the simulated period.

The loads act as concentrated forces for the chairs with passengers, which are in the loaded span section. They act as liner continuous loads at sections of both ropes that are also in this section.

3.3 Mathematical Background of the Simulation

Standard software for working with Finite Elements is used. Like most of the programs, using Finite Element Method, the movement of the bodies in the transport system, i.e. movement of the ropes and the chairs, one towards another when the ropeway is working can not be modeled. So the analysis is completed for a stationary ropeway.

Transient dynamic analysis for random lateral wind loads is completed.

Transient dynamic analysis is a technique used to determine the dynamic response of the structure under the action of any general time dependent loads.

The basic equation of motion solved by transient dynamic analysis is:

$$[M]\{\ddot{U}\}+[C]\{\dot{U}\}+[K]\{U\}=\{F\}$$

where:

$[M]$ - structural mass matrix;

$[C]$ - structural damping matrix

$[K]$ - structural stiffness matrix

$\{\ddot{U}\}$ - nodal acceleration vector

$\{\dot{U}\}$ - nodal velocity vector

$\{U\}$ - nodal displacement vector

$\{F\}$ - applied load vector

One of the methods used by the ANSYS program for solving this equation method is the Newmark time integration method. It is used for implicit transient analysis and is described in [1]. There the conditions of achieving of conditional stability of the solution are described. If there is no damping, the lack of numerical damping can be undesirable in that the higher frequencies of the structure can produce unacceptable levels of numerical noise, so a certain level of numerical damping is usually desired. The initial conditions are input by performing a static analysis load step (only dead loads are applied), prior to the start of the transient analysis itself. The initial displacements possess nonzero values and the initial velocity and acceleration vectors are zero.

A full transient nonlinear analysis is completed. The convergence of the solution is achieved by applying Newton-Raphson Procedure, along with the assumptions of the Newmark method.

The difficulty is to obtain a converging solution regarding the movement of the rigid chairs and the nonlinear dynamic reaction of the ropes. The possibility of large displacements appearing in the system, due to a high degree of flexibility of the ropes, must also be taken into account.

4. NUMERICAL DATA FOR THE CITED RESULTS

In this section some simulation results are presented.

In order to simulate the chair ropeway "Sliven-Karandila", geometric data and specifications were used (fig. 4).

The values of some parameters used in simulation are given in table 1:

Table 1

geometric data	
Horizontal distance between the two columns	80.8 m
Vertical distance between the two columns	26 m
Distance between the chairs	32.4 m
Diameter of the carrying rope	0.032 m
Diameter of the pulling rope	0.016 m
data concerning the chairs	
Mass of the empty chair	65 kg
Mass of the passengers in the first chair	160 kg
Mass of the passengers in the second chair	80 kg
Mass of the passengers in the third chair	0 kg
Z coordinate of the mass centre of the first chair	0.1 m
Z coordinate of the mass centre of the second chair	-0.3 m
Z coordinate of the mass centre of the third chair	0 m
Distance between the left column and the nearest chair *x* (fig. 3)	10 m
data concerning the wind loads	
Maximal value of the wind velocity V_{MAX}	20 m/s
Left limit of the section with wind loads ***wl*** (fig.3)	20 m
Right limit of the section with wind loads ***wr*** (fig. 3)	50 m

During the calculation the lateral wind loads change in time. Mathematical functions were used for the numerical simulation. The wind loads are proportional to the square of the wind velocity V_{MAX} and a time dependent sin – function [10] was used in the presented simulation. Mathematically, the type of the wind function is expressed in the following way:

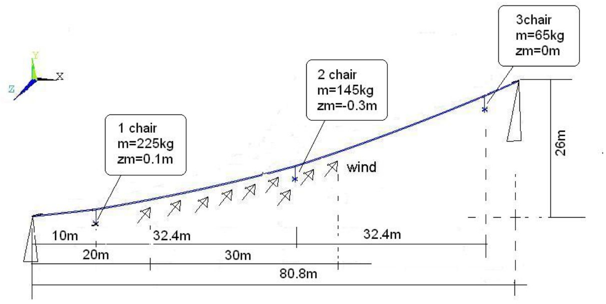

Figure 4. Some of the numerical data used in cited simulation

$$W_i(t) = \begin{cases} 0 & \text{if} \quad 0 < t < 1\,\text{s} \\ -W_{\text{MAX}} \sin\dfrac{\pi(t-1)}{2} & \text{if} \quad 1\,\text{s} \le t \le 3\,\text{s} \\ 0 & \text{if} \quad 3\,\text{s} < t < 6\,\text{s} \\ W_{\text{MAX}} \sin\dfrac{\pi(t-6)}{3} & \text{if} \quad 6\,\text{s} \le t \le 9\,\text{s} \\ 0 & \text{if} \quad t > 9\,\text{s} \end{cases}$$

whether:

$$W_{\text{MAX}} = \frac{A_{Wi}\, c_{Wi}\, \rho V_{\text{MAX}}^2}{2}$$

where

- A_{Wi} is the area exposed to the wind load (different for each rope and chair);
- c_{Wi} is the air drag coefficient (different for each rope and chair);
- ρ is the density of the air.

The time dependency of the wind loads is shown in fig. 5. It is assumed as load acting on a certain part of the span – between the $20^{\text{-th}}$ and $50^{\text{-th}}$ metres of the span. The horizontal length of the wind influence is established to 30m (fig. 4).

Usually the damping matrix $[C]$ is calculated as:

$$[C] = \alpha[M] + \beta[K]$$

In the simulation the α-damping (mass matrix

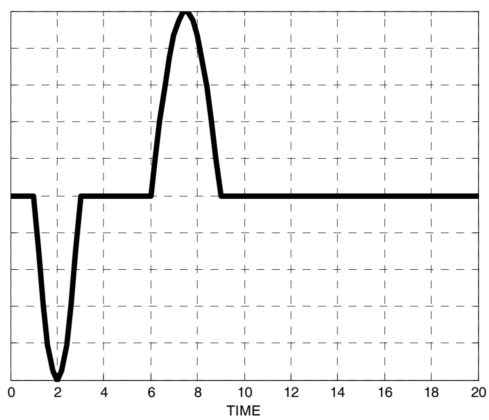

Figure 5. Time dependence of the wind function in the presented numerical simulation

multiplier) is set to zero as it is recommended in [1]. When completing a dynamic kinematic analysis it is not preferable to use α-damping, as it will dampen the rigid body motion of the system and it has been already said that chairs were treated like rigid bodies.

So, here $[C] = \beta[K]$. The stiff matrix multiplier β defines to some extent the material characteristic of the system. The accepted for calculations value is $\beta = 0.0025$ and is taken on the basis of numerical data given in the verification manual of ([1]). However, it must not be forgotten that the coefficient β is only a type of mathematical coefficient, which tries to model in a mathematical way the damping property of the material.

During the simulation a full transient non-linear analysis is completed.

5. RESULTS OF THE SIMULATION

Some of the obtained results are graphically presented in the following figures:

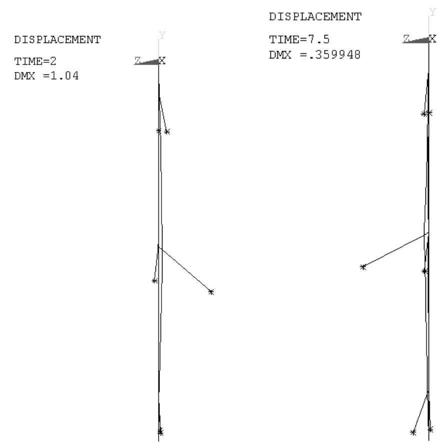

Figure 6a. time $t = 2$ s **Figure 6b. time $t = 7.5$ s**

Figure 6. Deformed and undeformed forms of the ropeway system at $t = 2$ s and $t = 7.5$ s, without damping, [m]

The projections in plane ***yz*** of the undeformed and deformed forms of the elastic transport system at time $t = 2$ s and at time $t = 7.5$ s, viewed against axis ***x***, are shown in fig. 6. The oscillating angle of the different chairs can be seen. At that time the horizontal deflection of the ropes is slight.

In the graphs in fig. 7 the stiffness damping multiplier β is zero and there is no damping in the simulated motion. In the following graphs (fig. 8) the damping coefficient β equals 0.0025 and damping is regarded. Each chair has been modeled as a pendulum with two DOFs – horizontal displacement of the clamp (the hanging point of the pendulum) and the rotation around it (the oscillating angle of the chair). The rotation is calculated for each step of the solution.

When both figures are compared, it can be seen that:

- the horizontal motion of the clamps without (fig. 7a) or with (fig. 8a) damping is very small;

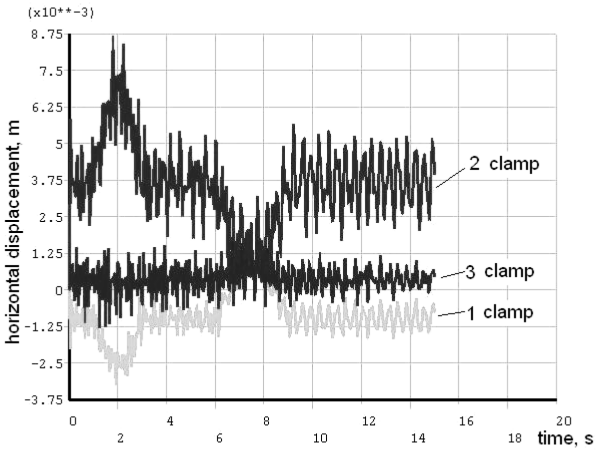

Figure 7a. Laws of the horizontal motion of the clamps without damping

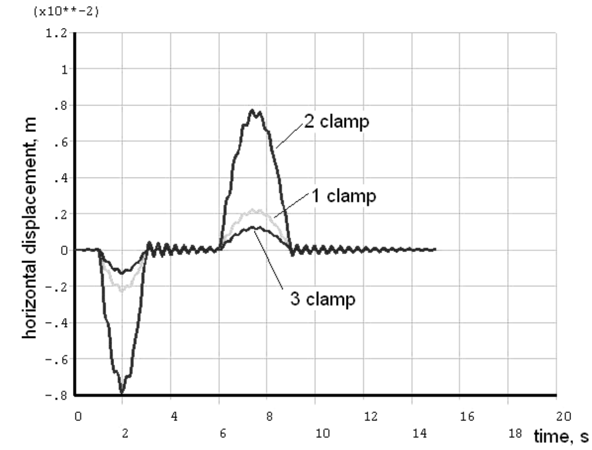

Figure 8a. Laws of the horizontal motion of the clamps with damping

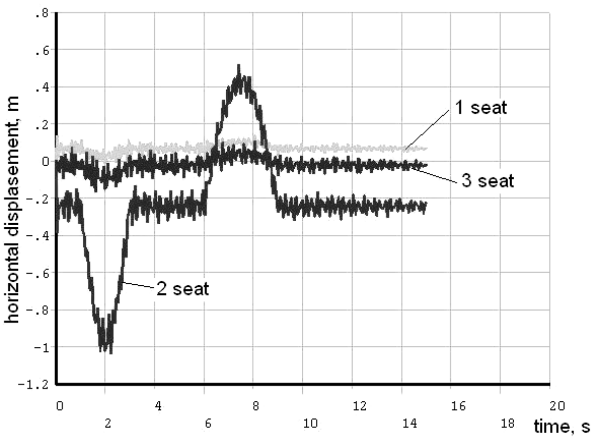

Figure 7b. Laws of the horizontal motion of the seats without damping

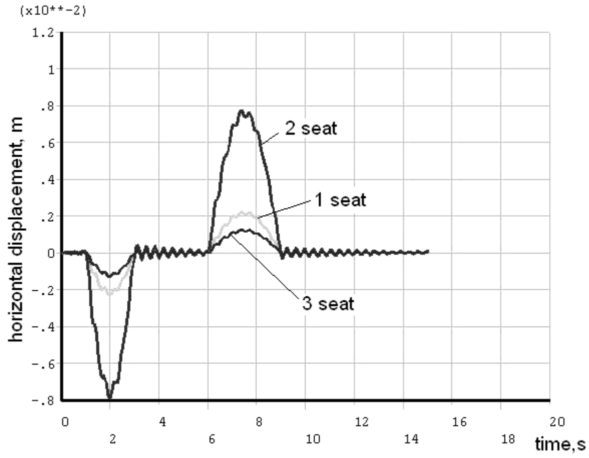

Figure 8b. Laws of the horizontal motion of the seats with damping

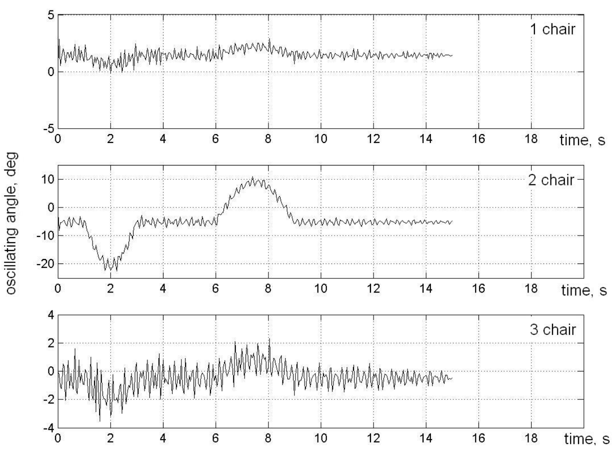

Figure 7c. Laws of the oscillating angle of the chairs without damping

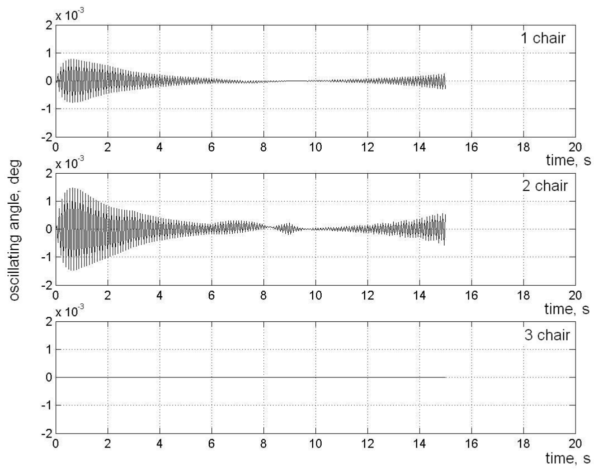

Figure 8c. Laws of the oscillating angle of the chairs with damping

Figure 7. Some kinematic characteristics of the motion without damping of the ropeway transport system during the simulated period of 15 s

Figure 8. Some kinematic characteristics of the motion with damping of the ropeway transport system during the simulated period of 15 s

• the horizontal motion of the seats without damping (fig. 7b) is much greater than the one obtained with damping (fig. 8b);

• the oscillating angle with damping is almost zero (fig. 8c).

• there is one main vibration corresponding to the function of the wind and some smaller ones summed to it;

• the additional vibrations (the above mentioned smaller ones) in the system are almost zero when there is damping (fig. 8);

• the stiffness damping multiplier β acts much more over the oscillation angle than over the horizontal motion of the clamp.

6. CONCLUSION

In order to check the validity of the created Finite Element model, a similar Finite Element model, but with different values of the parametric sets, has been created. It simulates the behaviour of another gondola ropeway, which has been functioning for some years now and for which there are measurements of the wind loads and the oscillation angles of the gondolas [6, 7]. An acceptable coincidence between the measured results and the numerical examples has been found. So it can be said that the numerical model of a ropeway transport system presented here, based on a Finite Element formulation, is appropriate and can be applied to additional ropeway transport systems.

The obtained results demonstrate that the behaviour of a ropeway, exposed to lateral wind loads is hard to investigate, regarding the nonlinearity of the model, because there are some numerical traps due to complexity of the input parametric sets. One of these traps is the exact value of the stiffness damping multiplier β, which strongly influences the convergence of the calculation process and affects the stability of the numerical simulation. Another, referable to the value of β, numerical trap is the desired level of numerical damping in order to prevent the numerical noise in the higher frequencies. As for engineering purposes, the higher frequencies can be omitted. This trap is not so important for models like the presented one.

As the obtained numerical results prove, having referred to the measurements, it is possible for the stiffness damping multiplier β to be omitted in the simulation process. Thus again the already existing engineering practice for this coefficient to be omitted is confirmed.

The presented model is a starting point for more complex analysis of the dynamic reaction of a working ropeway exposed to random lateral wind loads in which the stability of the simulated process is of primary importance.

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ДИНАМИЧКА АНАЛИЗА СЕДЕЖНИЦЕ ИЗЛОЖЕНЕ СЛУЧАЈНОМ ОПТЕРЕЋЕЊУ ОД ВЕТРА

Радостина Петрова

У раду је формиран коначно - елементни модел за анализу динамичке реакције седежнице, изложене случајном бочном оптерећењу од ветра. Поменути нумерички подаци односе се на жичару близу града Сливена у Бугарској. Посебна пажња посвећена је проблему који се односи на занемаривање пригушења.