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TRANSMISSION SHAFTS VIBRATIONS IN TRANSIENT ROTATING MODES

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The paper presents the investigation results of the transmission shaft dynamic behavior in transient modes of motion with change of the rotational speeds. It is shown that when the speed of rotation changes, in the inertial coordinate system, during the acceleration time this process continues with growth of oscillation frequency.

Keywords: inertia forces, dynamic stability, numeric differentiation, transmission shaft vibration, rotational speeds.

Introduction. The tasks of dynamics in systems that include transmission shafts arise during the structural elements of machines and devices are designed. The oscillatory motion of such elastic shafts during rotation is described by complex systems of differential equations in partial derivatives taking into account the gyroscopic forces, which are caused by transfer, relative and Coriolis accelerations. Often such shafts are run in modes with different rotational speeds. Because of it the study of such rotational systems behavior during the acceleration time interval is interesting.

In recent years, the problems of the shafts and rotating rods dynamics have been studied in the works of various authors.

The paper [6] is concerned with the dynamic behavior of the rotating composite shaft on rigid bearings. A-version, hierarchical finite element is employed to define the model. A theoretical study allows the establishment of the kinetic energy and the strain energy of the shaft, necessary to the result of the equations of motion. In this model the transverse shear deformation, rotary inertia and gyroscopic effects, as well as the coupling effect due to the lamination of composite layers have been incorporated. A hierarchical beam finite element with six degrees of freedom per node is developed and used to find the natural frequencies of a rotating composite shaft.

In paper [7] is analyzed the method of transfer matrix, set up the lumped parameter model. Then figure out the common transfer matrix of shaft. Take some shaft as an example, using MatLab is calculated the critical speed. The analysis can provide basis and method for shaft vibration numerical simulation.

An analytical method to solve vibration of the propulsion shaft under hull deformation excitations is introduced in paper [8]. The model of shaft with the excitations at bearings is seen as a simplified propulsion shaft-ship hull system, as bearings could be assumed as the connection structures that transmit the forces from hull to shaft. The equations of shaft motion and continuity/boundary conditions are presented and hull excitations are included in the continuity conditions equations. Vibration characteristics of shaft under hull excitations are gained. The effects of propeller, supports stiffness, the location of hull excitations, the amplitude of excitations and the size of shaft are discussed.

In paper [10] authors try to focus on the analysis of the effects produced on the whirling shaft of different diameters while running at the different speeds. The objective of the study is to find the effect of different diameters rotating at different speeds on the amplitude and natural frequency of the shaft. Also forced vibration analysis of the shaft is done. Some parameters are also studied that are responsible for the failure of the system before breakdown, and the effect of the resonance frequency of the shaft.

The task of rotating shaft oscillations is studied in paper [14], too. The shaft is viewed with non-uniform cross-sections per length.

The viewed results analysis that are presented in the scientific literature shows, that in many works the attention is paid to the critical rotational speeds calculation and frequencies of natural oscillations determination with various system parameters. But meanwhile there is the reason to examine the transient modes of rotation with change of rotational speeds and how this act influences to oscillatory motion. Therefore, the study of such systems dynamic behavior in transient rotating modes becomes interesting.

This work examines the dynamic behavior of transmission shafts when the rotational speed changes.

Problem statement. When the transmission shafts are run there are cases when the speed of their rotation can be changed forcibly. This process can be accompanied by vibration with change of frequency and amplitude of shaft transverse oscillations. In this way as a dynamic model is considered a rod with length l (Fig. 1). The rod is rotated on angular speed ω_t around the rectilinear axis O_1X_1 of the stationary coordinate system $O_1X_1Y_1Z_1$.

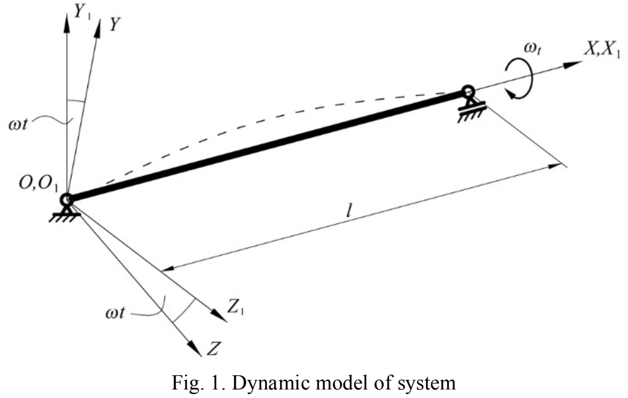


Fig. 1. Dynamic model of system

The rotating coordinate system *OXYZ* is tied to the rod and rotates with it. The direction of *OX* axis coincides with direction of O_1X_1 axis. Axis of rod in deformed state is coincided with the *OX* and O_1X_1 axis. The oscillatory motion of the rod in the *OXYZ* coordinate system is characterized by $y(x,t)$ and $z(x,t)$ displacements of the points, that belong to the axis of rod in the *OY* and *OZ* coordinate axes' direction, respectively.

The mathematical model of rotating with constant angular speed rod transverse oscillations in coordinate system *OXYZ* is described by system of differential equations, which have a form [2]:

$$\begin{cases} EI_1\dfrac{d^4y}{dx^4} - \bar{m}r^2\left(\dfrac{d^4y}{dt^2dx^2} + \omega_t^2\dfrac{d^2y}{dx^2}\right) - 2\omega_t\bar{m}\dfrac{dz}{dt} - \bar{m}\omega_t^2 y + \bar{m}\dfrac{d^2y}{dt^2} = 0 \\ EI_2\dfrac{d^4z}{dx^4} - \bar{m}r^2\left(\dfrac{d^4z}{dt^2dx^2} + \omega_t^2\dfrac{d^2z}{dx^2}\right) + 2\omega_t\bar{m}\dfrac{dy}{dt} - \bar{m}\omega_t^2 z + \bar{m}\dfrac{d^2z}{dt^2} = 0, \end{cases} \quad (1)$$

where E – elastic modulus of rod's material; I_1, I_2 – inertia moments of rod section in mutually perpendicular planes; r – radius of gyration; $\overline{m}$ – mass of unit per length; ω_t – rotational speed of rod around the axis that coincides with the axis of rod in undeformed state.

The system of equations (1) is valid in the time interval when the rod rotates at a constant speed ω_c during the time interval t_c. During the time interval t_a, when the speed of rotation is being changed, the motion occurs with angular acceleration ε and as a result the tangential component of the transfer acceleration of the rod element $dx\ \vec{a}_e^{\tau}$ appears. It should be taken into account in the system of equations (1) by the $-\overline{m}\ \varepsilon z$ and $\overline{m}\ \varepsilon y$ components, respectively.

Technique. To study of the dynamics of investigated objects in this paper the technique that is described in papers [3, 4] is used. In this technique the process of oscillation is modeled based on repeated (cyclic) solving the system of differential equations for every point of system in order to find the new coordinates of positions for these points in each next point of time $t+\Delta t$.

The technique is realized by computer program with graphic user interface that is developed by authors. That program lets to study the dynamics of modeled system by calculating and drawing the current bend forms of the rotating rod in oscillation. Also, program lets to make the analysis of behavior of modeled system, find the dynamic instability regions, draws the diagrams of it.

Results. In this paper, using said program, the study of the transmission shaft dynamics is done. The considered shaft is tubular, outer diameter d = 60 mm, wall thickness s = 15 mm. Length of shaft is equal to 3 m. The shaft operation is reviewed on different rotational speeds with change of it in certain time period with specified acceleration.

For this shaft with set parameters, the first critical speed of rotation is equal to 166 s^{-1}. On the diagrams (Fig. 2-5) the graphs of shaft vibration are presented in the three ranges of time: time of rotation at constant initial speed before acceleration – t_i; time of rotation with acceleration – t_a; time of rotation at constant final speed after acceleration – t_f). Namely, in the ranges of before-critical speeds (50-100 s^{-1}, 50-150 s^{-1}) and in the range of speeds (100-200 s^{-1}) when the rotating shaft is being passed through the critical speed by different accelerations.

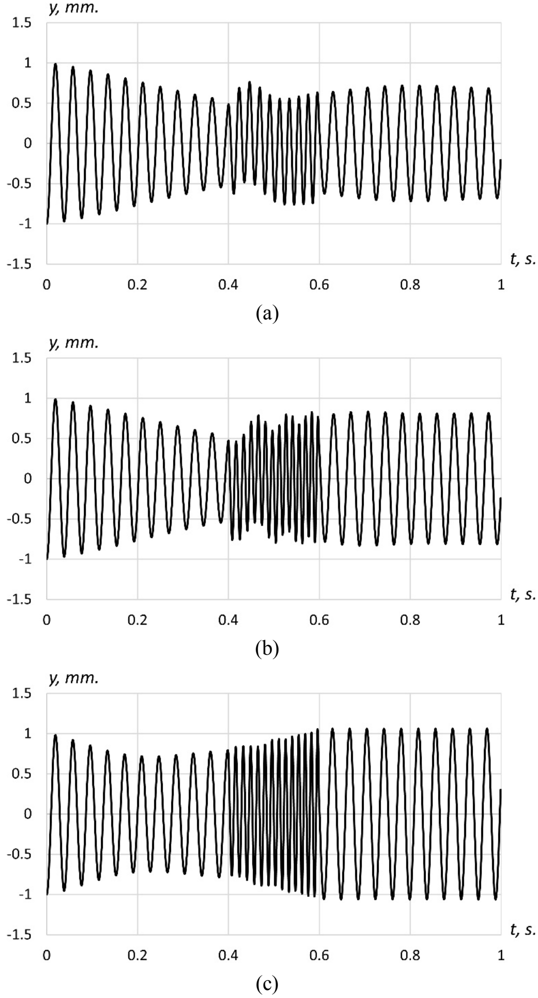
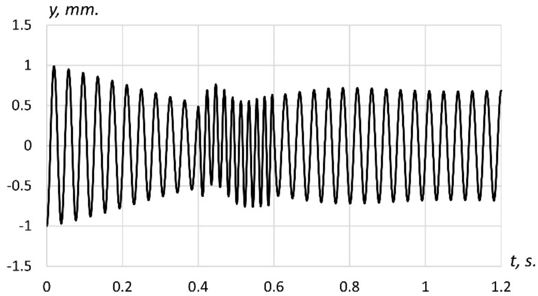


Fig. 2. Shaft vibration with change of speed:
(a) from 50 to 100 s^{-1}; (б) from 50 to 150 s^{-1}; (в) from 100 to 200 s^{-1}

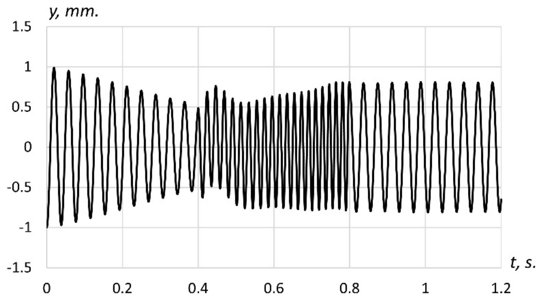
Specifically on diagrams in Fig. 2 the shaft oscillations in the inertial coordinate system are shown when the rotational speed changes in the acceleration time interval t_a=0.2 s^{-1}. As we can see from all of tree presented cases, during the time when rotational speed increases, the frequency of oscillation increases significantly compared to the time intervals of rotation at constant speed.

The shaft oscillations in the inertial coordinate system when the rotational speed changes by acceleration ε=250 s^{-2} are shown on diagrams in Fig. 3.

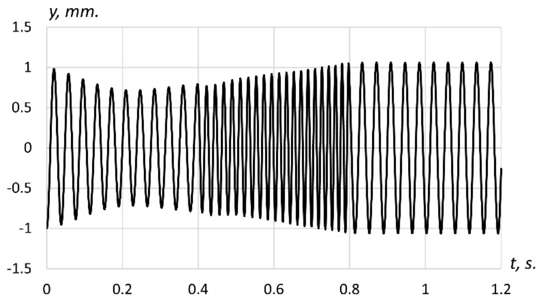
Same graphs of the shaft oscillations when the rotational speed changes by acceleration ε=200 s^{-2} are presented in Figure 4. Similar, the oscillations when the rotational speed changes by acceleration ε=100 s^{-2} are shown in Fig. 5.



(a)



(b)



(c)

Fig. 3. Shaft vibration with change of speed by acceleration ε=250 s^{-2}:
(a) from 50 to 100 s^{-1}; (b) from 50 to 150 s^{-1}; (c) from 100 to 200 s^{-1}

It can be seen from the diagrams that in each of the three presented cases, during the acceleration time the frequency of oscillation increases significantly compared to the time intervals of rotation at constant speed. Also, all graphs show that the increase of the rotational speed leads to increase of oscillation amplitude. After pass to next constant speed of rotation, the frequency of oscillations, as shown in diagrams, decreases back.

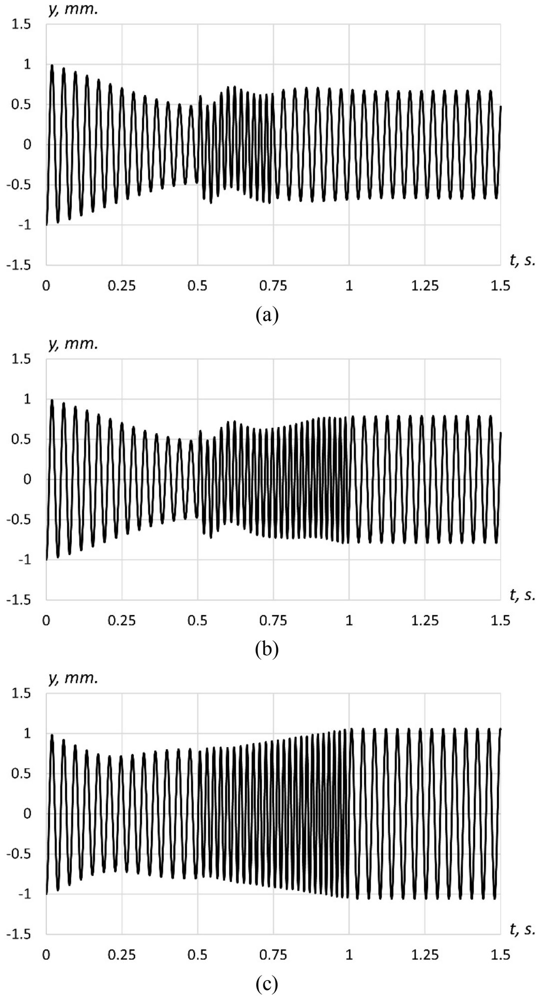
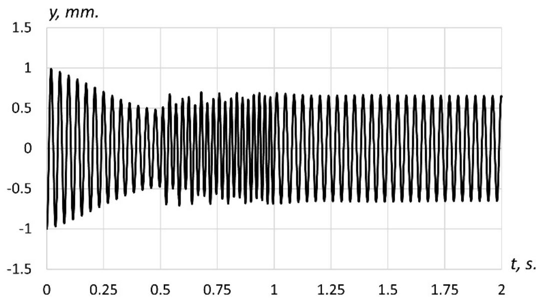
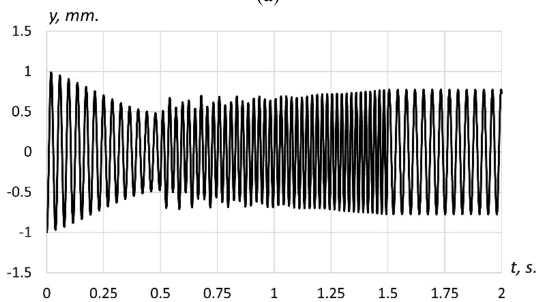


Fig. 4. Shaft vibration with change of speed by acceleration ε=200 s^{-2}:
(a) from 50 to 100 s^{-1}; (b) from 50 to 150 s^{-1}; (c) from 100 to 200 s^{-1}

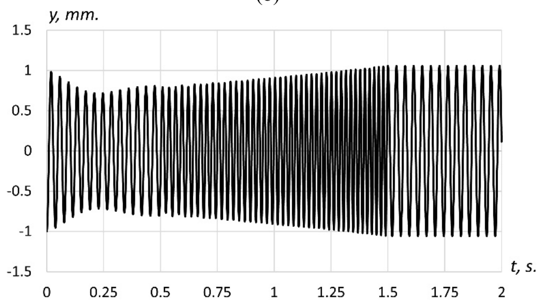
Conclusion. The presented research results of transmission shafts rotation with change of the rotating speeds show that when the rotational speed changes, namely at the time interval of its increase, in the inertial coordinate system this process continues with growth of oscillation frequency during the acceleration time. The amplitude of oscillations in this time increases, too. After pass to next constant speed of rotation, the frequency of oscillations, as shown in diagrams, decreases back. Such increase of oscillation frequency



(a)



(b)



(c)

Fig. 5. Shaft vibration with change of speed by acceleration ε=100 s^{-2}:
(a) from 50 to 100 s^{-1}; (b) from 50 to 150 s^{-1}; (c) from 100 to 200 s^{-1}

during the acceleration can lead to undesirable consequences of destructive nature.

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ВІБРАЦІЇ ТРАНСМІСІЙНИХ ВАЛІВ ПРИ ПЕРЕХІДНИХ РЕЖИМАХ РУХУ

В роботі наведені результати дослідження динамічної поведінки трансмісійного валу в перехідних режимам руху із зміною швидкості обертання. Такі режими руху виникають при експлуатації трансмісійних валів, що передають крутний момент від двигуна до виконавчого пристрою. Цей процес може супроводжуватись вібрацією валів із зміною частоти та амплітуди коливання. У зв'язку з цим актуальним є питання вивчення динамічної поведінки таких систем, виявлення впливу на них руху із зміною швидкості обертання. Дослідження здійснено використовуючи розроблене програмне забезпечення, в якому реалізована методика комп'ютерного моделювання коливального руху стержнів, що обертаються, під дією інерційних навантажень. Таке програмне забезпечення дозволяє моделювати коливальний рух валів, а також визначати параметри, при яких може відбутися втрата динамічної стійкості змодельованої системи. За допомогою зазначеного програмного забезпечення побудовані діаграми, що відображають графіки коливального руху стержня, яким моделюється робота трансмісійного валу, при встановлених параметрах системи. Процес коливального руху розглянуто у просторі. Математична модель коливального руху при обертанні описана системою диференціальних рівнянь у рухомій системі координат, що обертається разом із валом, а графіки коливального руху наведені в інерційній системі координат. Показано, що при зміні швидкості обертання, а саме в момент її збільшення, цей процес триває зі збільшенням частоти коливання протягом часу прискорення. Також показано, що при цьому відбувається збільшення амплітуди коливань. Після встановлення сталої швидкості обертання частота коливань, як відображено на графіках, знов зменшується. Таке збільшення частоти коливань під час прискорення може призвести до небажаних наслідків руйнівного характеру.

Ключові слова: інерційні навантаження, динамічна стійкість, чисельне диференціювання, вібрація трансмісійного валу, змінна швидкість обертання.

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TRANSMISSION SHAFTS VIBRATIONS IN TRANSIENT ROTATING MODES

The paper presents the investigation results of the transmission shaft dynamic behavior in transient modes of motion with change of the rotational speeds. Such modes occur during the transmission shaft transmits torque from engine to executive device. This process can be accompanied by vibration with change of frequency and amplitude of shaft oscillation. Therefore, the question of studying the dynamic behavior of such systems with identifying the impact of rotational speeds changing on them is relevant. In this regard, the study was done by developed software, in which a technique of computer simulation of the oscillating motion of considerable rotating rods under the action of inertia forces is implemented. Such software gives the possibility to model the oscillatory motion of rotating rods and determine the parameters by which the dynamic stability loss of the studying system can occur. Using this software, the diagrams of rod oscillating motion of the rotating shaft were drawn for definite parameters of the considered system. The process of oscillation is considered in space. The mathematical model of transverse oscillations is described by system of differential equations in rotating coordinate system that is tied to the shaft, but diagrams of oscillations is shown in inertial coordinate system. It is shown that when the speed of rotation changes, namely at the time interval of its increase, this process continues with growth of oscillation frequency during the acceleration time. Also shown that the amplitude of oscillations increases, too. After pass to next constant speed of rotation, the frequency of oscillations, as shown in diagrams, decreases back. Such increase of oscillation frequency during the acceleration can lead to undesirable consequences of destructive nature.

Keywords: inertia forces, dynamic stability, numeric differentiation, transmission shaft vibration, rotational speeds.

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В роботі наведені результати дослідження динамічної поведінки трансмісійного валу в перехідних режимам руху із зміною швидкості обертання. Показано, що при зміні швидкості обертання, а саме в момент її збільшення, цей процес триває зі збільшенням частоти коливання в інерційній системі координат протягом часу прискорення.
Табл. 0. Іл. 5. Бібліогр. 11 назв.

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Tabl. 0. Fig. 5. Ref. 11.

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