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DYNAMICS OF ROTOR SYSTEMS UNDER SEISMIC EXCITATION

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The paper presents the general theory of dynamic systems analysis under kinematic excitation. On its basis the methodology of analysis of rotor systems of general type being under seismic excitation was developed. The results of unsteady dynamic analysis of one degree of freedom system and a rotor supported by non-linear journal bearings are presented. The methodology and the algorithms are implemented into the Dynamics R4 program system developed to analyze the dynamic behavior of complex rotor systems.

KEY WORDS: seismic excitation, rotor, nonlinear supports, modeling, unsteady analysis, Dynamics R4

Introduction

Nowadays more attention is paid to reliability and safety of machines operating in the exploitation areas with a higher seismic activity and particularly to gas turbine plants to drive turbogenerators. Gas turbine plants and their equipment have to sustain seismic excitation at equal or more than 7 points on the MSK-64[1] scale. At the same time the more exacting requirements may be made to gas turbine plants.

The most widely spread method to analyze seismic stability of gas turbine plants at the design stage is mathematical modeling of dynamic loads and deformations (response to the seismic excitation) appearing in them. The task belongs to the class of the tasks of rotor systems analysis under kinematic excitation.

The theory of kinematic excitation is quite thoroughly developed in the general machine dynamics. Taking it into account the tasks of movement of wheeled and track-type traffic [2] are investigated, the vibration measure elements – seismometers and accelerometers, etc. – are designed. The deep study of rotor dynamics under seismic excitation started at the beginning of 60-s in 19 century when the new requirements were made to the design of nuclear stations [3]. Seismic analysis of rotor systems is significantly different from structural seismic analysis. First of all, it takes relation to rotation of rotors and their elastic characteristics: the presence of gyroscopic forces at rotation of rotors, significant Coriolis forces appearing on rotors at angular movements of foundation, presence of the supports with nonlinear elastic and damping characteristics, significant unbalances, etc.

The [4], [5] papers notice the significant influence of rotation on displacement and reactions in supports. Meanwhile, this influence is much smaller for rigid rotors than for flexible rotors. This allows using the modal analysis methods for rigid rotors with low rotating speeds by reducing the mode numbers in solution and solving task for nonrotating rotor at steady statement. The [6] paper gives significant correlation between foundation movement and dynamics of flexible rotor. The [7] work notices that in order to obtain the exact solution it is necessary to use the complete spectrum of frequencies and modes. Meanwhile, contribution of modes with back precession prevails over contribution of modes with forward precession in rotor dynamics.

Dynamic response of a rotor system is significantly influenced by characteristics of supports. It is obvious that a rotor supported by journal bearings has smaller vibration displacements and loadings from seismic excitation in comparison with rolling bearings. At the same time at applied shock such rotor becomes unstable at the regime exceeding first critical rotating speed twice as many [8]. Works [9], [10] consider increase in seismic stability of rotor systems by selection of supports characteristics at design stage.

The present paper develops the methods of analysis of complex rotor systems under multiple-factor seismic excitation. The theory of the methods and the results of their application for simple dynamic system (harmonic oscillator) and for rotating rotor supported by nonlinear journal bearings at unsteady setting are presented.

Composition of seismic signal

The Russian State Standard 30546.1-98 [11] includes data about generalized seismic loads for products (also for loads) differentiated for different seismic areas. As a rule, this information is presented as an excitation spectrum (vibration acceleration) in different directions. The acceleration value in vertical direction accounts for 0.7 of the acceleration value in horizontal direction.

Figure 1 shows an example of spectrum consisting of 4 harmonics and corresponding to the earthquake intensity of 9 for zero foundation point.

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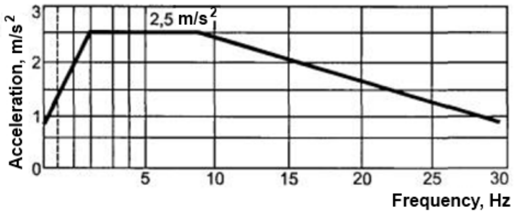


Figure 1. Maximum acceleration amplitude versus frequency of sinusoidal vibrations (an excitation spectrum) for horizontal direction

Table 1 shows the frequency and acceleration values for characteristic points according to the Figure 1.

Table 1

Frequency, Hz	0.5	2.0	10.0	30
Acceleration, m/s^2 (g)	0,15 (0,015)	2,5 (0,25)	2,5 (0,25)	1 (0,1)

The Standard also sets the factor of relative damping ζ of seismic excitation that is equal to 5%.

The foundations of the theory of kinematic excitation

The foundations of the theory of kinematic excitation may be presented by giving an example of harmonic oscillator. The generalized equation of movement of harmonic oscillator at unsteady setting may be given as the following:

$$m \cdot \ddot{y}_s(t) + c \cdot \dot{y}_s(t) + k \cdot y_s(t) = S_g(t) \quad (1)$$

where S_g – seismic forces. According to the superposition principle

$$S_g(t) = k \sum_1^n y_{g(i)}(t) \quad (2)$$

where n – the number of harmonics in the excitation spectrum.

The following nonlinear function describes each harmonic

$$y_g(t) = Ye^{-\zeta\omega t} \cdot \sin(\sqrt{1-\zeta^2}\,\omega t + \varphi), \quad (3)$$

where $y(t)$ – current value of harmonic function; Y – vibration amplitude; e – exponent; ζ – factor of relative damping; ω – frequency of harmonic signal; φ– initial phase; t – current time.

Conversion of accelerations into displacements may be done according the following

$$|Y| = 9.81 \cdot g / \omega^2 \quad (4)$$

Dynamic equation in the matrix form for a nonlinear rotor system with n degrees of freedom under seismic excitation is presented below:

$$[M]\cdot\{\ddot{q}(t)\} + [C]\cdot\{\dot{q}(t)\} + [K]\cdot\{q(t)\} = \\ = \{F_d(t)\} + \{R_в(t)\} + \{S_g(t)\} + \{W\} \quad (5)$$

where $[M], [C], [K]$ – square matrixes of inertia, damping and stiffness of a rotor system obtained by discretization of a rod finish-element method model; $\{\ddot{q}(t)\}, \{\dot{q}(t)\}, \{q(t)\}$ – acceleration, speed and displacement column-vectors; $\{F_d(t)\}$- column-vector of unbalance forces; $\{R_в(t)\}$- column-vector of bearing reactions; $\{S_g(t)\}$- column-vector of seismic forces; $\{W\}$- forces of gravity.

The equation (2) in matrix form is presented below:

$$\{S_g(t)\} = \sum_i [K]\{y_{g(i)}(t)\}, \quad (6)$$

where i – a number of a harmonic of a seismic spectrum.

It should be noticed that only some terms of a $\{S_g(t)\}$ matrix are not equal to zero – for the degrees of freedom that belong to suspension (supports) of a rotor system.

The special methods of solution of the (5) equation allow its reducing. For example, even for the systems with multiple degrees of freedom the modal methods allow creating of an equations system that may be easily solved by the methods of unsteady analysis – by means of direct integration of movement equations [12]. At such an approach the behavior of a dynamic system is calculated for the sequential time intervals with dynamic characteristics determined at the beginning of the considered interval. New dynamic characteristics are obtained using the models of nonlinear elements. Input data of the models are displacements and speed of points through which nonlinear elements are connected with the rest of a dynamic system; output data are dynamic reactions. Force influence may also change.

Results of analysis of oscillator model

The methodology described above is implemented in the Dynamics R4 program system [13] that allows obtaining movement equations for the most complex rotor systems including the great number of different nonlinear elements and unsteady loads changing according to the given law.

To analyze behavior of a harmonic oscillator under seismic excitation the mathematical model was developed in Dynamics R4. Figure 2 presents its graphically.

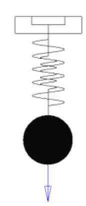


Figure 2 Model of harmonic oscillator

Table 2 presents data of the harmonic oscillator.

Table 2

Parameter	Value
Mass, kg	100
Spring stiffness, N/m	1e7
Spring damping, N*sec/m	1000

The model has two links. One of them is auxiliary; it serves for calculation of a basis set of frequencies and forms of the oscillating system (in compliance with the theory of modal analysis). The other link simulates unsteady action on the foundation of the oscillating system. Through this link the seismic excitation is set as a spectrum of accelerations (frequency, amplitude, phase, stiffness and damping characteristics of foundation).

Figure 3 shows amplitude-time characteristics at displacement for the harmonic oscillator depending on seismic excitation of harmonics spectrum (table 1) if there is no damping of a signal in vertical direction Y.

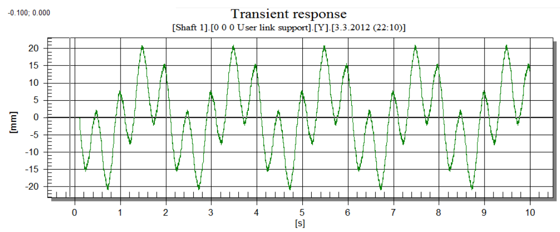


Figure 3 Harmonic oscillator response on polyharmonic excitation (ζ=0)

Figure 4 shows the corresponding harmonics spectrum according to acceleration.

If the spring stiffness is high then response of the oscillator is analogous to excitation. It means that seismic forces are completely passed on the oscillator mass. Oscillator vibrations from seismic excitation may be reduced by selection of the spring stiffness.

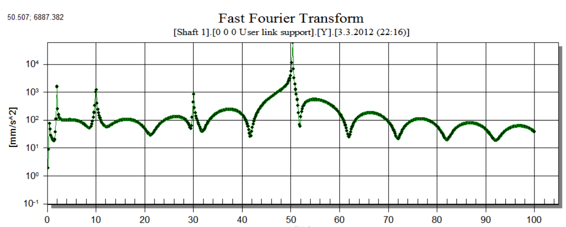


Figure 4 Vibration spectrum of harmonic oscillator (ζ=0)

Table 3 presents response of the harmonic oscillator of mass at the spring stiffness k=1e7 N/m. Frequency of 50.35 Гц corresponds to undamped frequency of oscillator natural oscillations.

Table 3

Frequency, Hz	0.5	2.0	10.0	30	50.35
Excitation acceleration, m/sec^2	0.15	2.5	2.5	1.0	-
Response acceleration, m/sec^2	0.076	1.58	1.21	0.85	6.88

Seismic excitation may be single, repeated at certain intervals, but always damped. Figure 5 presents amplitude-time characteristics according to displacement (Y direction) for harmonic oscillator from seismic excitation at relative damping coefficient of 5%.

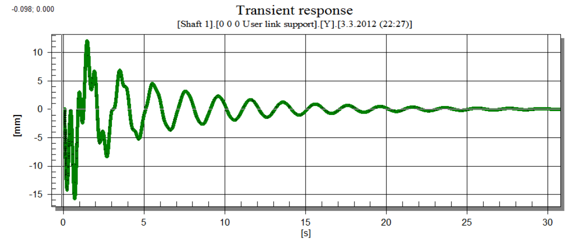


Figure 5 Response of the harmonic oscillator according to displacement (ζ=0.05).

Figure 6 shows similar response according to acceleration.

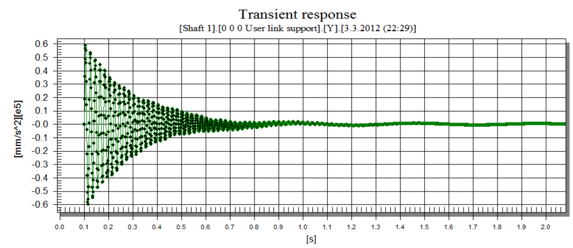


Figure 6 Response of harmonic oscillator according to acceleration (ζ=0.05).

Standards usually set that time of analysis of object under seismic excitation should be no less than 1 minute. Analysis shows that at this frequency spectrum of excitation of the investigated oscillator and 5% of damping the almost complete damping of oscillation takes place in about 30…60 seconds.

Rotor model

Figure 7 presents schematic rotor model taken from [9] to investigate its characteristics under seismic excitation.

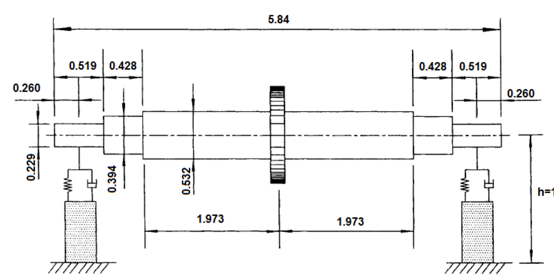


Figure 7 Rotor model

Table 4 presents the rotor data.

Table 4

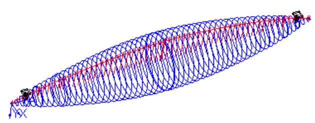
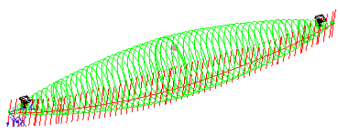
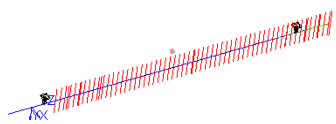
Disk	
Mass, kg	5670
Diametral momemt of inertia, , kgm^2	3550
Polar moment of inertia, kgm^2	7100
Shaft	
Modulus of elasticity, N/m^2	2.078x10^{11}
Density, kg/m^3	7806
Poisson's ratio	0.3
Rotating speed, rpm	880
Journal bearings	
Вязкость масла, Nsec/m^2	0.14839
Bearing diameter, m	0.229
Bearing length, m	0.229
Clearance, m	3.8x10^{-4}

Rotor	
Mass, kg	13578

At linear calculation the supports are simulated by the link with stiffness corresponding to the stiffness k~0.5e9 N/м of cylindrical journal bearings around operating mode *n*=880 rpm. Thrust bearing also has stiffness of 0.5e9 N/m. Bearings damping is conventional - 10000 Hc/м. Unbalance – 56000 gsm.

Frequency of natural oscillations of nonrotating rotor is equal to 1263 rpm. Table 5 shows critical speeds and rotor mode shapes.

Table 5

1262 rpm – shape of backward precession

1264 rpm – shape of forward precession

1796 rpm – shape of longitudinal oscillations


First and second shapes correspond to backward and forward rotor precession; third shape is one of longitudinal oscillations. It may be noticed that rotation of the investigated rotor does not virtually change frequencies of natural oscillations.

Results of rotor analysis under seismic excitation

Calculations were carried out at operating mode of n=880 rpm if there is no damping of seismic signal. Seismic excitation was implemented along X, Y and Z axes. The acceleration value in vertical direction accounted for 0,7 of acceleration value in horizontal direction.

Figure 8 presents amplitude-time characteristic of the dynamic rotor behavior, Figure 9 shows cascade diagram of vibration spectra (Y direction).

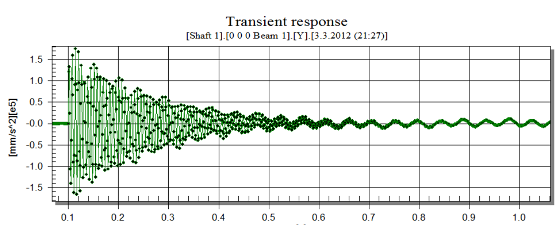


Figure 8 Amplitude-time rotor characteristic under seismic excitation (ζ=0)

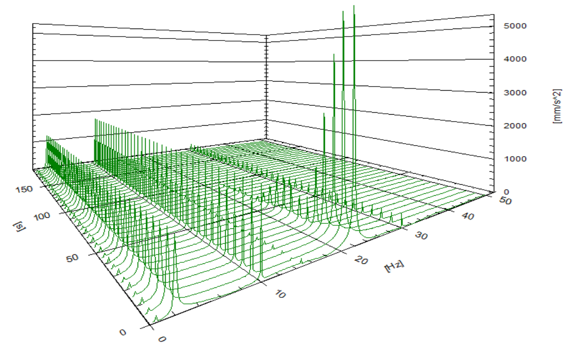


Figure 9 Cascade diagram of vibration spectra of rotor response on seismic excitation. Frequency of natural oscillations is damped

Figure 10 shows signal spectrum obtained at 5 second from the beginning of seismic excitation.

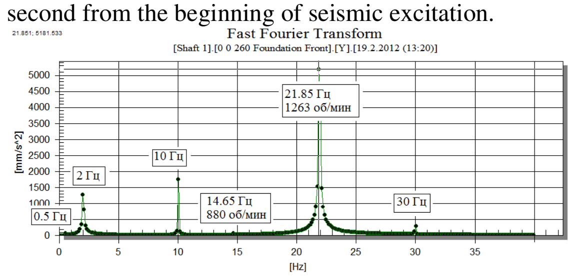


Figure 10 Spectrum of dynamic rotor response

All harmonics of seismic excitation, frequency of rotor vibrations and frequency of natural rotor vibrations may be highlighted at spectral characteristic.

Results of rotor analysis under damped seismic excitation

Calculations were carried out for rotating rotor at n=880 rpm and 5% of damping of seismic signal excitation. Figure 11 presents amplitude-time characteristic of dynamic rotor behavior (displacement), Figure 12 gives cascade diagram of vibration spectra (acceleration).

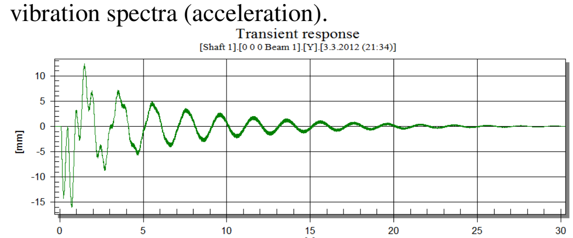


Figure 11 Amplitude-time characteristic under damped seismic load (ζ=0.05). Y direction.

Figure 12 shows that components of rotor vibrations are damped almost immediately, vibrations with natural frequency are damped during 60-100 seconds.

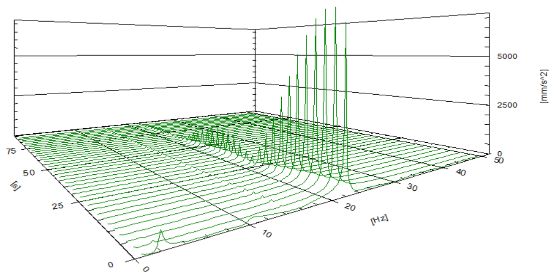


Figure 12 Cascade diagram of vibration spectra of rotor response on seismic excitation

Transient analysis of rotor supported by journal bearings

Beforehand nonlinear rotor characteristics were obtained, Figures 13, 14. Resonance rotor area from 1000 rpm to 1600 rpm may be highlighted at amplitude time characteristic. Stability loss happens at about 2700 rpm.

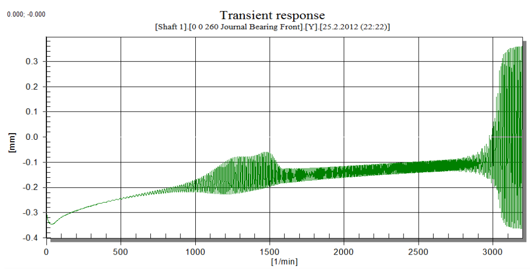


Figure. 13 Amplitude-time rotor characteristic in range from 0 to 4000 rpm

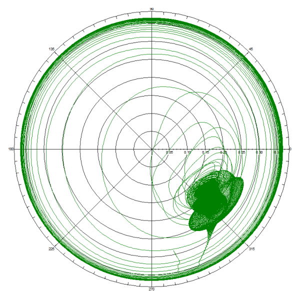


Figure 14 Orbits of rotor movement in range from 0 to 4000 rpm

Vibration spectrum includes 1X, 2X 3X harmonics, Figure 15.

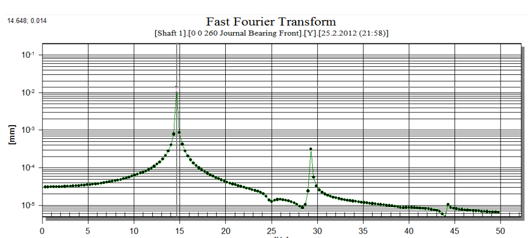


Figure 15 Spectrum of rotor harmonics at 880 rpm

Analysis of seismic influence on rotor was led for 2 cases. First calculation included investigation of dynamic behavior under undamped seismic excitation. Figure 16 presents broadband spectrum of the rotor frequencies according to acceleration under undamped seismic excitation. All the components of seismic excitation, natural vibrations frequency and rotating speed may be highlighted in the obtained spectrum.

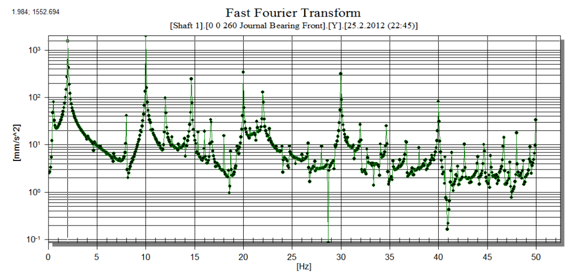


Figure 16 Spectrum of dynamic response of rotor supported by journal bearings

Second calculation considers the rotor dynamic behavior under damped seismic excitation, Figures 17, 18.

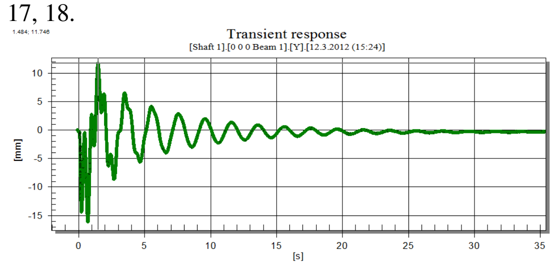


Figure17 Amplitude-time characteristic of rotor under damped seismic load (ζ=0.05*)*. Y direction

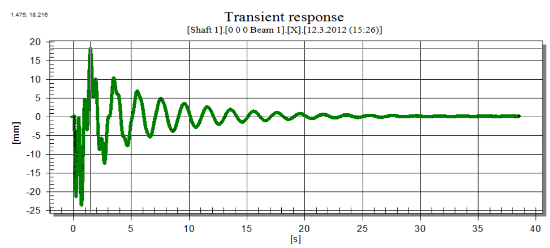


Figure18 Amplitude-time characteristic of rotor under damped seismic load (ζ=0.05*)*. X direction

Reactions appearing in journal bearings of the investigated rotor reach 255 tonnes in vertical direction, 330 tonnes in horizontal direction, Figures. 19, 20.

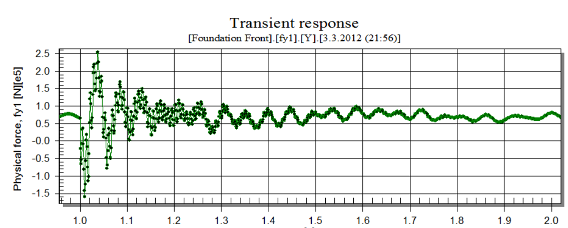


Figure 19 Reactions in rotor supports under damped seismic load (Y direction)

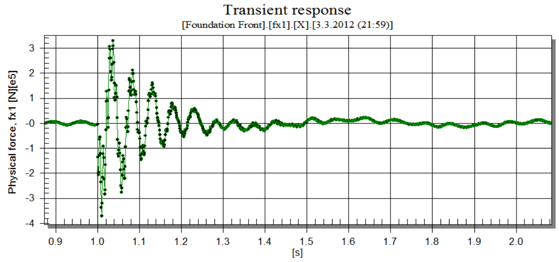


Figure 20 Reactions in rotor supports under damped seismic load (X direction)

Conclusion

The paper gives general theory of dynamic systems analysis under kinematic excitation at steady and unsteady setting. On its basis with consideration of Russian standards, the methodology of analysis of general rotor systems under seismic excitation was developed. The results of dynamic analysis of the system with one degree of freedom and the rotor supported by nonlinear journal bearings are given. The methodology and algorithm created on its basis are implemented in the Dynamics R4 program system developed to analyze dynamic behavior of complex nonlinear rotor systems at unsteady setting.

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