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CALCULATED INVESTIGATION OF THE BEAM VIBRATIONS WITH LOCAL SURFACE DAMAGE

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Abstract: *The paper presents the procedure for calculating the vibration characteristics of the beam structural element with a breathing crack. The beam of a rectangular cross-section with a triangular breathing crack is an object of investigation. From the proposed calculation procedure, the vibrodiagnostic parameters of the presence of a crack are obtained, namely, relative variation of the vibration frequency and ratios between the amplitudes of dominant harmonics under principal, super- and subharmonic resonances at different sizes of the crack. The ratio between the amplitudes of dominant displacement harmonics under subharmonic resonance is efficiently used as a factor of the presence of a breathing crack.*

Keywords: Cantilever beam, Breathing crack, Principal, Super- and subharmonic resonances, Vibration frequency.

1. Introduction

The design and manufacture of various types of machine parts involve the calculation of safety margins and the limits of safe operation. However, process, production, and operational defects cannot be avoided. They can cause damage such as nicks, dents, material chipping, erosion and corrosion damage, cracks, etc., and destroy both the component and the machine as a whole. Thus, during operation, there is a need for monitoring its technical condition for timely detection of possible damage. Destructive and nondestructive diagnostic methods are used to diagnose their presence and determine the parameters (dimensions, location). The main disadvantage of destructive methods lies in the need to dismantle the structure and the impossibility of its subsequent use. Therefore, nondestructive methods are more common, in particular, vibration damage diagnosis, which involves the relationship between the damage parameters and variations in the vibration characteristics of the structure as a whole or its elements.

For the appropriate use of vibration characteristics in vibration diagnostics, a comprehensive investigation of the vibration processes of systems with damage is required, where experimental (Yan et al, 2013), analytical (Matveev et al, 2018), and numerical (Broda, 2016; Kruts, 2018) investigations methods are used. Since such methods require significant material costs, while analytical methods allow one to investigate vibrations of only simple structural elements (beams, plates, etc.), numerical methods are the most promising. They make it possible to perform the detailed modeling of the object of investigation, as well as consider the loading conditions close to operational ones.

Depending on the type of damage and the choice of the vibration characteristic of the structural element, which are used to analyze the behavior, the vibrodiagnostic methods can be conditionally divided into linear and nonlinear ones. The former is based on monitoring the modal characteristics: frequency and mode of vibrations (Zinkovskii et al, 2018), vibration damping characteristics (Curadelli et al, 2008). More complex and effective methods are nonlinear ones used to detect the fatigue cracks: distortion of the harmonicity of

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the strain signal, super- and subharmonics multiples of the forced frequency of its vibrations, as well as nonlinear resonance modes (Giannini, 2013, Zhang, 2017).

The goal of this paper is the numerical investigation of the nonlinear vibration characteristics at the principal, super- and subharmonic resonances of the forced vibrations of the structural elements with a breathing crack.

2. Numerical Calculation of the Forced Vibrations of the Beam with a Breathing Crack

A cantilever beam of a rectangular cross-section with the following dimensions is considered: l = 0.23m, h =0.02m, b =0,004m (Fig. 1, a); with a surface triangular breathing crack with the depth of a = 0.01m (Fig. 1, b) at a distance of x_{cr}=0.1l of the beam fastening. The material properties are as follows: $E=2\cdot10^{11}$Pa, ρ=7800kg/m^3, μ=0.3, δ=0.01.

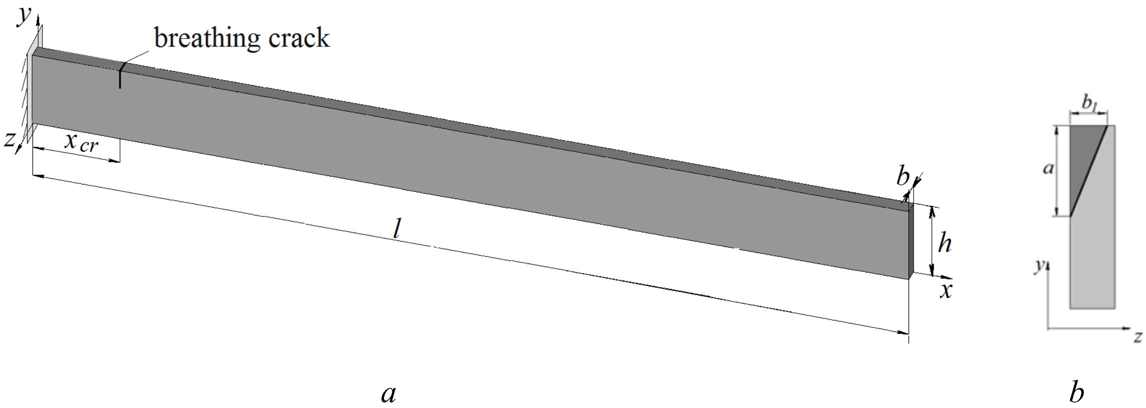


Fig. 1: Cantilever beam (a) and its cross-section with a crack (b).

The numerical determination of the vibration characteristics of the beam with a breathing crack is based on plotting its geometrical and 3D finite element (FE) model. FE calculation model involves eight-node elements, each node has three degrees of freedom, which allows one to determine the displacement within any node of the beam along each of its axes.

The surface breathing crack is a mathematical cut, where the conditions of interaction between the contact crack surfaces are satisfied. In case the surfaces are not in contact, the crack is fully closed, and it is open at their contact. When the surfaces are in partial contact, there is a transition process as crack opening-closing.

The required initial, limit, and loading conditions are specified for the developed FE model.

The characteristics of forced vibrations are determined using the Newmark method. It involves the dividing of the total time of vibration into a certain number of steps, the displacement of the beam is determined for each step. The investigation requires the correct time interval of the forced vibrations of the structural element with the selected energy dissipation coefficient in the system, which allows one to establish the steady-state mode of the resonance vibrations (Fig. 2).

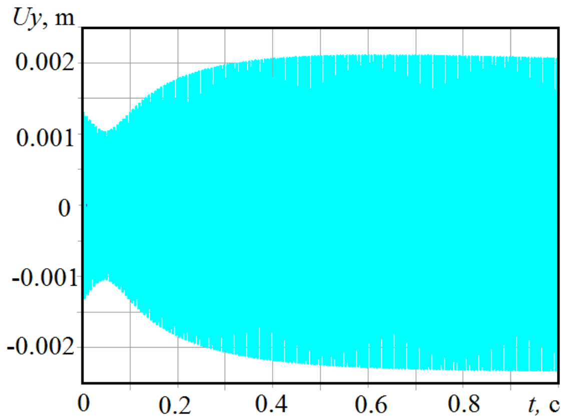


Fig. 2: Time-dependent displacement of the beam free end with a crack.

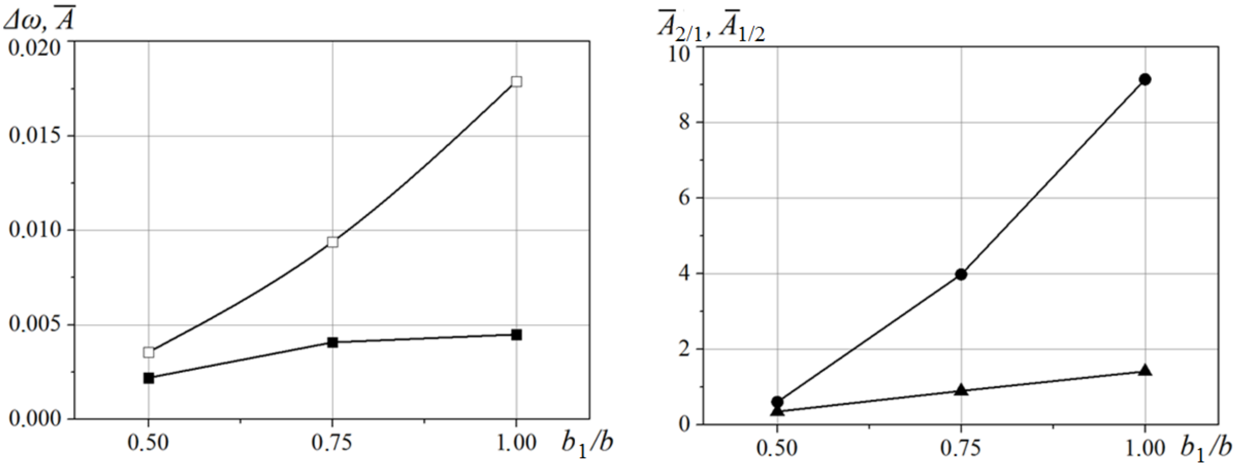
To determine the resonance frequency and spectrum of the amplitudes of vibrations, the obtained time-dependence of displacement of the selected node of the structural element was processed employing FFT analysis.

3. Results of Investigations

The calculations of the determination of the influence of the parameters of the breathing crack on the vibration characteristics of the cantilever beam were performed for the principal ($\nu=\omega$), superharmonic resonance of 1/2 order ($\nu=0.5\omega$) and subharmonic resonance of the second order ($\nu=2\omega$) of the first flexural mode of vibrations, where ν, ω are the excitation frequency and resonance frequency of vibrations of the beam with a crack.

The forced vibrations were induced by harmonic force $P_0 \sin(\nu t)$ applied to the beam free end.

Based on the performed numerical investigations at the frequency of principal resonance, the dependencies of the relative variation of the vibration frequency of the beam with a crack were obtained $\Delta\omega=1-\omega/\omega_0$, where ω_0 is the natural frequency of vibrations of the undamaged beam, $\overline{A} = A_2 / A_1$ are the relations of the amplitudes of the dominant harmonics of displacement of the beam free end, where A_1 and A_2 are the first and second displacement harmonics (Fig. 3, *a*).



a *b*

Fig. 3: Dependencies of the relative variation of the vibration frequency (□) and ratio between the amplitudes of dominant harmonics (■) at principal resonance (a), as well as ratio of the amplitudes at super- (▲) and subharmonic (●) resonances (b)

It can be concluded that the use of the presented vibration characteristics at the principal resonance is inefficient for the vibration diagnostics of the crack presence since the monitoring of the frequency variation and analysis of the second harmonic of the vibration amplitude are rather difficult due to their low value.

The nonlinear resonance modes at the frequency of super- and subharmonic resonances are more susceptible. Figure 3, b illustrates the dependencies of the variation of the ratio between the amplitudes of dominant harmonics $\overline{A}_{2/1} = A_2 / A_1$ at superharmonic resonance and $\overline{A}_{1/2} = A_1 / A_2$ at subharmonic resonance depending on the relative width of the triangular breathing crack. The obtained vibrodiagnostic parameters are significantly higher at the specified nonlinear resonance as compared with those obtained at the principal resonance, which shows its efficiency for the diagnostics of the breathing cracks.

4. Conclusions

The procedure of the numerical determination of the vibrodiagnostic parameters of the surface breathing crack in the beam specimen during the excitation of the principal, super- and subharmonic resonance of the flexural mode of vibrations was developed. The relative variation of the vibration frequency and the ratio between the amplitudes of the dominant harmonics were determined at the specified resonance modes for different lengths of the crack, as well as different damage areas. It is shown that the ratio between the amplitudes at subharmonic resonance is the most efficient in the determination of the presence of a crack and its dimensions.

The proposed numerical calculation procedure allows one to obtain the vibration characteristics of the structural elements with a breathing crack of arbitrary shape. It also makes it possible to yield more insight into the specific features of vibrations of mechanical systems with a breathing crack. The obtained results can be used in the design of practical methods of vibration diagnostics of fatigue damage in the structural elements.

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