Determination of frequency characteristics of thin-walled rods with transverse cracks

A Gavrilov¹, G Grebenuk², and N Morozov¹

¹Orenburg State University, Faculty of architecture and construction, 13 Pobegy avenue, Orenburg, 460018, Russian Federation
²Novosibirsk State University of Architecture and Civil Engineering (SIBSTRIN), Institute of construction, 113 Leningradskaya Street, Novosibirsk, 630008, Russian Federation

E-mail: *pialex@bk.ru

Abstract. Vibrations of a thin-walled cantilever rod of a box-shaped profile were studied. The natural vibrations frequencies of a rod with a crack of different depth and located in different places of the rod were determined. The method of conducting an experiment using a vibration analyzer is given. A variant of determining the location of the crack depending on the change in the natural vibrations frequency is proposed. The resulting expression for estimating the location of the crack has an error of no more than 2.7 percent of the length of the rod, which makes it effective in practical application. The puchnost points of each oscillation form of the cantilever rod are determined, taking into account internal friction, which allowed us to specify the locations of sensors for maximum efficiency in evaluating the influence of crack parameters on natural frequencies. We found that when the crack is located in the places where the puchnosty for the corresponding vibration form causes noticeable energy dissipation due to friction in the crack.

1. Introduction

The widespread use of thin-walled metal rod structures makes it necessary to develop methods and tools for diagnosing defects that occur in these structures during operation. The most common defects will be cracks. The causes of cracks are different: from imperfections in the manufacturing processes of structures to fatigue and corrosion of metals during operation. In this regard, developments aimed at detecting cracks in thin-walled metal rod structures are very relevant.

Currently, many studies have been devoted to the study of the cracks influence on changes in the dynamic characteristics of beam structures [1 – 5]. In these works, various models of a cracked beam are proposed. Some of these models take into account a decrease in overall stiffness, while others take into account an increase in flexibility. Waveform graphs are widely used to detect structural damage. However, most of these models use the coefficient of stiffness reduction, which is a fairly rough approximation. It is established that the method of simple stiffness reduction is applicable only to thick beams.

Nonlinear vibration methods used for finding cracks allow using forms of higher and subharmonic vibrations. However, the non-linearity of the characteristics appearing in this case may be associated with an incorrect choice of boundary conditions or measurement errors, and may have no relation to the cracks [6 – 9]. However, research shows that non-linearities in cracked rods are particularly strong in the vicinity of damage. This makes it possible not only to determine the position of the cracks, but also to determine the differences in the nonlinearities caused by the crack from the nonlinearities obtained due to other causes.
The increased flexibility resulting from a crack can be modeled by a weightless spring, and the increased damping can be modeled by a weightless damper located at the crack site. This allows you to calculate the vibration damping coefficient. The effect of a crack on mechanical energy dissipation depends on the depth of the crack, its location, and internal friction in the metal. Multiple cracks in beams can be detected using a method based on the strain energy [9].

Thus, it is possible to further optimize the search for the location of cracks based on the analysis of changes in the natural frequencies of vibrations. The analysis of natural vibration frequencies of rods without taking into account cracks is described in [10]. The purpose of this study is to obtain regression dependencies of crack locations on the frequencies of lower forms of vibration of rods based on experimental studies.

2. Methods and Materials

The experiment was conducted using the method of indicating the resonance of the structure using a microwave generator GOST 30630.1.1-99 "Test methods for resistance to mechanical external factors of machines, devices and other technical products. Determination of the structuredynamic characteristics" was to fix the values of natural frequencies with the use of vibration analyzer "Vibrat 3.2". The used sensors are 352C04.

The test samples were rods from a rolled profile manufactured according to GOST 8645-68. Material-St3ps steel (analog to BS standard: 1449-27/23CR).

The rods were firmly pinched at one end. A thread with a fixed weight of 4 kg was fixed at one of the points. In the future, the thread was cut and the frequencies of its own vibrations were recorded.

The crack was modeled as a section 1 mm wide and 2.5, 5, 7.5 and 10 mm deep.

To analyze the results, we used methods of mathematical statistics, in particular, regression analysis.

3. Experimental Part

Algorithm for conducting tests in accordance with the applied methodology:

1) the method of fixing the test sample is selected;
2) selected the site of attachment of the sensors;
3) after fixing the sample and installing sensors, excite beam vibrations;
4) according to the data obtained, determine the natural frequency of vibration of the beam.

Magnetic sensors were installed on the upper side of the test rod, and the cables from them were attached to the suspension. Suspension is necessary to exclude the influence of the wire mass on the oscillating system. The sensors were connected to the ports of the Vibran-3 vibration analyzer in the order of numbering.

Using the device's vibration analyzer, vibrations were recorded over four channels in a specified time interval with manual start-up. Data from the vibration analyzer was transferred to a PC, and oscillation graphs (figure 1) and spectral graphs were constructed using special software.

Since the vibration analyzer has a certain sensitivity, the first four forms of vibrations were studied and the locations of the puchnosty - zones of maximum deviations of the beam particles from the static equilibrium position were determined (figure 3). To determine points of the loops of each form, was investigated by a differential equation of the vibrations of thin-walled beams. In contrast to existing methods for studying beam vibrations, internal friction was taken into account in this case [10], which made it possible to specify the locations of the beams using a program specially created for this purpose.
Then the samples are installed in the stand. At a distance of 250 mm from the free edge, a weight of 4 kg is fixed on the rope, the knots of the load attachment to the beam are centered. The measuring device selects the range of measured frequencies and the time of measurement. To reduce the impact of various errors, measurements are made in 2 ranges: 0.5-100 Hz and 5-1000 Hz; measurement time: 10 s and 2 s (respectively). When all the add-ons are completed, the measurement command is given and at the same time, the thread holding the load is cut. There are damped harmonic vibrations, which are read by measuring devices attached to the test sample. After the measurement is completed, a graph of the oscillation amplitudes of this measurement is plotted on the device screen.

30 measurements were made for each sample. First, the beam vibrations are measured without a crack, 3 measurements in 2 frequency ranges. Further, at the specified distance for a specific beam, a cut was made with a depth of h = 25 mm, for which 3 measurements are also made in 2 frequency ranges. Then the cut is deepened in increments of 25 mm, until a depth of 100 mm is reached. These operations were performed for each rod.

Figures 4-9 show spectral graphs of the eigenfrequencies of rods with relative crack depths h=1/10, h=2/10, h=3/10, h=4/10, h=5/10, h=6/10, where the relative crack depth was taken as the ratio of the crack depth to the cross-section height of the rod.
Figure 3. Spectral graph of natural frequencies of rod vibrations, $h=1/10$.

Figure 4. Spectral graph of natural frequencies of rod vibrations, $h=2/10$.

Figure 5. Spectral graph of natural frequencies of rod vibrations, $h=3/10$. 
Figure 6. Spectral graph of natural frequencies of rod vibrations, h=4/10.

Figure 7. Spectral graph of natural frequencies of rod vibrations, h=5/10.

Figure 8. Spectral graph of natural frequencies of rod vibrations, h=6/10.
The graphs show that in the presence of a crack, the frequencies of all 4 forms decrease. The relative decrease in the frequency of vibrations for each of the forms is shown in Table 1.

The results of measurements are shown in Table 1.

**Table 1. Relative decrease in the frequency of vibrations (percent).**

| Crack depth | 1 mode | 2 mode | 3 mode | 4 mode |
|-------------|--------|--------|--------|--------|
| h=1/10      | 0      | 2      | 1      | 1      |
| h=2/10      | 0      | 6.2    | 2      | 5.3    |
| h=3/10      | 2.5    | 8.96   | 1      | 8      |
| h=4/10      | 5      | 12.4   | 1      | 11.6   |
| h=5/10      | 2.5    | 22.7   | 2      | 13.2   |
| h=6/10      | 5      | 25.5   | 2      | 16.4   |

4. Results

Table 1 shows that the largest decreases in frequency values are obtained for the second and fourth forms of oscillation. This is due to the fact that the location of the crack coincides with the place of origin of the beam for the corresponding vibration form, which in turn causes noticeable energy dissipation due to friction in the crack. The greater the amplitude, the greater the dissipation and the greater the attenuation of the vibrations.

Regression analysis was performed to determine the location of the crack. The dependence of the crack location on the frequencies of the first lower four oscillation forms in the form of (1) polynomial was established.

\[ x = \sum B_{ijkm} v_i v_j v_k v_m. \]  \hspace{1cm} (1)

Here *i, j, k, m = (1, 2, 3, 4)* is the frequency sequence numbers.

It is found that for the console rod in question, the coefficients have the values shown in Table 2.

**Table 2. Indexes for determining the position of the crack.**

| The index of the coefficient | Value    |
|-----------------------------|----------|
| 1                           | -0.0610  |
| 2                           | 0.0756   |
| 3                           | 0.0608   |
| 4                           | 0.2392   |
| 11                          | 0.0057   |
| 22                          | -0.0072  |
| 33                          | -0.0119  |
| 44                          | -0.0097  |
| 12                          | -0.0117  |
| 13                          | 0.0089   |
| 14                          | -0.0138  |
| 23                          | 0.0127   |
| 24                          | -0.0007  |
| 34                          | -0.0093  |

Using the polynomial (1) allows you to get the location of the crack with an error of no more than 2.7 percent of the rod length.
5. Conclusions

Thus, the following results were obtained in this study:

1. The puchnost points of each oscillation form of the cantilever rod are determined taking into account internal friction, which allowed us to specify the locations of sensors for maximum efficiency in evaluating the influence of crack parameters on natural frequencies.

2. It was found that when the crack is located in the places where the puchnosty for the corresponding vibration form causes a noticeable energy dissipation due to friction in the crack: the greater amplitude, the greater the dissipation and the greater the attenuation of the vibrations.

3. The resulting expression for estimating the location of the crack has an error of no more than 2.7 percent of the length of the rod, which makes it effective in practical application.

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