Natural frequencies of a vertical pipeline element

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Abstract. This work is devoted to the problem of noise and vibration from the pipeline systems in multi-storey buildings. A method for determining the probability of the occurrence of increased vibrations using modal analysis in the ANSYS Workbench software package is proposed. Numerical analysis of straight sections of the pipeline, each differing in diameter and length, is performed. The results of the numerical analysis of the influence of the length, diameter, and wall thickness of a pipe system element on the change in the frequencies of its natural oscillations are presented with a view to predicting the risk of possible resonance regimes. Pairwise and multiple regression analyses are performed, and regression equations are obtained describing the functional relationship between the first frequency of the natural oscillations and the length, diameter, and wall thickness of the pipeline section.

1. Introduction

The 21st century has become the century for the intensive development of building technological systems and the introduction of effective innovative technologies in the construction industry with the goal of creating buildings that have the highest degree of comfort – multi-comfort.

A building technological system should be understood as a set of interrelated elements in an engineering system, united by a single constructive and technological solution aimed at improving the quality, reliability, durability, and efficiency of the construction [1].

The newest technological ideas differ from older ones, first of all, by the fact that they are oriented towards creating the most comfortable working and living conditions. The embodiment of such ideas in building (engineering) systems is, as a rule, of a qualitative nature.

One of the tendencies in the modern development of large cities is the constant growth in the number of storeys, which has arisen in connection with the need to increase the spaciousness of cities, a consequence of the growth of the urbanization index.

At present, the majority of unsolved engineering tasks requiring considerable expenditure on empirical research are an important component of scientific and technological progress. Therefore, computer modeling in combination with the use of numerical methods is an efficient and affordable way for analyzing similar problems.

This article is directly related to the solution of one such problem in the design and operation of the engineering systems of multi-storey apartment buildings - the emergence of noise and vibration in pipeline systems.
The Rospotrebnadzor Office often receives complaints from apartment owners located above individual heat points (ITPs) in the cellars of multi-storey buildings and residents of apartments adjacent to communication and ventilation mines. As a rule, prolonged exposure of the human body to noise and vibration causes functional changes in internal systems and organs. It also causes significant psychological stress, which ultimately affects the general condition of the body. It is also worth noting that, due to vibration, communications at home may suffer.

In building design, the modal analysis method for studying the vibrations of building structures has been widely used. Nevertheless, only the experimental and analytical modal analysis methods, described in the works of G. Mikota, A.F. D'Souza, G.M. Makaryants, D.J. Ewins, J.C. Wachel, J.D. Tison, X. Li, J.J. Nieter et al., were used to solve the vibration problems of hydraulic systems [2-16].

G. Mikota’s results provide a theoretical basis for the experimental modal analysis of hydraulic pipelines. They demonstrate how standard experimental modal analysis procedures can be adopted for hydraulic pipelines if mobility input is replaced with the frequency response functions between flow rate excitation and pressure response. Following these considerations, the experimental modal analysis of hydraulic pipeline systems shall be carried out in practice [2-5].

For example, in [8] it is shown that the study of the pipeline system’s vibroacoustic response is prone to fail the reliable causation of elevated dynamic loads when based only on Fourier analysis of the working fluid pulsation and pipeline vibration. It is suggested that we complement vibroacoustic response analysis with the calculation of modal parameters. A mathematical computation of the modal frequencies and shapes was implemented instead of experimental observation in order to exclude the undesired signal introduced with attached mechanical equipment. On top of this, the mathematical computation of the pipeline modal parameters allowed us to perform a pipeline modal frequency shift from the water-hammer effect frequency range through cautious relocation of additional supports.

Paper [17] presents estimates of the acceptability of vibrations, together with methods for troubleshooting piston compressors, pumps, and/or pipelines to determine whether problems are caused by pulsation or mechanical resonances. The main principles of pulsation generation and control are presented. The authors believe that the key to designing and operating safe piping systems is to control the pulsation levels and separate the mechanical natural frequencies from the pulsation excitation frequencies.

In this paper, a method is proposed for determining the probability of the occurrence of increased vibrations in pipeline systems using numerical modal analysis in the ANSYS Workbench 12.0 software package. This program complex is used for conducting numerical experiments in various fields of industry (mechanical engineering, agrarian industry) [18-21]. However, it has not been used for carrying out experiments of this kind for pipeline systems.

Through conducting ANSYS-based modal analysis for a ditch device, the authors of [18] obtained the natural vibration frequency and response effect of the ditch device (during field work, the vibration frequency of the ditch device was 8-9HZ). The natural frequency of the ditch device completely avoided the machine vibration frequency in the seeding period, and thus avoided the poor working conditions caused by resonance.

The method of numerical modal analysis for analysing the frequencies of fluctuations in rod basic insulators is described in [19]. Using the method of free fluctuations as a form of diagnosis, it was found that the main difficulty is the choice of the informative frequency ranges of the spectrum characterizing the existence of defects. The ANSYS software package was used for final element modeling.

The fundamentals of the ANSYS Workbench software in engineering analysis are described in [22, 23]. A modal analysis on the numerical model of the pipeline system element using the ANSYS PC for the purpose of determining the frequencies and modes of the element's natural vibrations was considered in [24].

In the most modern software systems, modal analysis is the solution to the problem of free oscillations in a discrete system by the finite element method [25-27].
The purpose of this work was to study the influence of the geometric parameters of an element of the pipeline system on its resistance to vibrations.

To achieve this goal, the following tasks were set:
1) Conduct a numerical modal analysis of the dynamic parameters of the elements of a pipeline system of various geometric parameters.
2) Determine the dependence of the first critical frequency of natural oscillations on the geometric parameters of an element of the pipeline system.
3) Perform regression analysis and obtain regression equations that describe the functional relationship between the first natural frequency and the length, diameter, and wall thickness of the pipeline section.

2. Method

The elements of a pipeline system, like most structures, make mechanical fluctuations. The modal analysis method is used to calculate the dynamic characteristics of pipeline elements: the frequency and shape of natural oscillations. The oscillations take place with an initial deviation from the equilibrium state of one of the system parameters and the subsequent absence of an external variable effect on the system. The "dynamic individuality" of the system is determined by its behavior with free vibrations, which characterizes the behavior of the system in other conditions.

A determination of these kinds of parameters makes it possible to assess the degree of danger of possible resonance regimes occurring when dangerous harmonics enter the operating range of the acting external loads (harmonic analysis). As a rule, the source of the forced oscillations in this case is that the pumping units have large capacities.

Modal analysis of the processes for determining N’s frequencies and shape modes is performed on the basis of the oscillation equation (1):

\[ [M]\ddot{\mathbf{x}} + [C]\dot{\mathbf{x}} + [K]\mathbf{x} = 0 \]  

where [M], [C] and [K] are the mass, damping and stiffness of the structure in the matrix form [20].

If we neglect the damping effect, we obtain an equation of the form (2):

\[ [M]\ddot{\mathbf{x}} + [K]\mathbf{x} = 0 \]  

3. Results

In this paper, numerical modal analysis of the dynamic parameters of the pipeline system elements of various geometric parameters was carried out in ANSYS Workbench PC. The first ten frequencies and forms of natural oscillations for different sections of the pipeline were determined as shown in Figure 1.

The values of the outside diameter of the pipes (mm) are taken in accordance with GOST 10704-91 "Pipes steel electrically welded straight. Assortment": 15 × 1.0; 15 × 1.2; 15 × 1.4; 15 × 1.5; 15 × 1.6; 20 × 2.0; 25 × 2.0; 32 × 2.8; 40 × 3.0; 48 × 3.0; 60 × 3.8; 70 × 4.0; 102 × 5.0; 114 × 5.0; 140 × 5.0; 168 × 5.0; 180 × 5.0; 219 × 6.0. The lengths of the calculated straight sections of the pipeline system lie in the range 1.0 ÷ 6.0 m.

To determine the equations (mathematical models) that most closely describe the experimental data, two types of regression analysis (pair and multiple) were performed using MS Excel.

For the regression analysis, only the first (critical) frequency was used since it has the smallest value; therefore, it is the most dangerous in the case of resonance regimes.

The main purpose of regression analysis is to determine the analytical form of communication, in which the influence of one (simple regression analysis) or several (multiple regression analysis) factors cause a change in the outcome.
Figure 1. Forms of the natural oscillations of a 6-meter straight section of the pipeline system with an external diameter of 114 mm and a wall thickness of 5.0 mm filled with water: (a) the 1st form; (b) the 2nd form; (c) the 3rd form; (d) the 4th form; (e) the 5th form; (f) the 6th form; (g) the 7th form; (h) the 8th form; (i) the 9th form; (k) the 10th form.
In this paper, a simple (pairwise) regression analysis was performed for two cases: determining the dependence of the value of the first frequency of natural oscillations on the diameter of the pipeline section \( F_1 = f(d) \) and on the length of the pipeline section \( F_1 = f(l) \).

Preliminary analysis showed that the dependence in both cases is non-linear.

The coefficient of determination is the main criterion characterizing the degree of quality of the regression model describing the relationship between variables. Its value lies in the interval: \( 0 \leq R^2 \leq 1 \). Thus, when \( R^2 = 1 \) - the coupling is functional and the regression model explains 100% dependence and change of the investigated parameter Y from independent factors X. It is considered permissible to accept the regression model for \( R^2 \geq 0.8 \).

Analyzing the results of simple (paired) regression analysis, we can draw the following conclusions:

1. There is a dependence of the first natural oscillation frequency on the diameter and length of the pipeline section.

2. The regression equation describing the dependence of the first frequency of natural oscillations on the diameter of a pipeline section has the form of a sixth-order polynomial function. For pipeline sections with a length of 1.5; 3.0; 6.0 m, the equation of the dependence of the first frequencies of the natural oscillations on the diameters (Figure 2), respectively, has the form of equations (3), (4), (5):

\[
F_{1,1.5} = 7 \cdot 10^{-10}d^6 - 5 \cdot 10^{-7}d^5 + 0.0001d^4 - 0.02d^3 + 1.4416d^2 - 47.107d + 684.56
\]

\[
F_{1,3.0} = 3 \cdot 10^{-10}d^6 - 2 \cdot 10^{-7}d^5 + 6 \cdot 10^{-5}d^4 - 0.0088d^3 + 0.6254d^2 - 20.924d + 299.41
\]

\[
F_{1,6.0} = 1 \cdot 10^{-10}d^6 - 1 \cdot 10^{-7}d^5 + 3 \cdot 10^{-5}d^4 - 0.0038d^3 + 0.267d^2 - 9.0641d + 129.4
\]

Figure 2. Graphs of the dependencies of the first frequencies of natural oscillations on diameters for sections of pipelines 1.5, 3.0, 6.0 m in length and their regression models.
3. The regression equation describing the dependence of the first frequency of natural oscillations on the length of the pipeline section has the form of a power function. The equation of the dependence of the first frequencies of natural oscillations on the lengths (Figure 3) has the following form of equations (6), (7), (8), (9), (10), (11) for the diameters 32, 48, 70, 114, 168, 219 mm, respectively:

\[
F_1 = 283.74l^{-1.479} 
\]  
(6)

\[
F_1 = 370.12l^{-1.773} 
\]  
(7)

\[
F_1 = 533.05l^{-1.905} 
\]  
(8)

\[
F_1 = 901.94l^{-1.931} 
\]  
(9)

\[
F_1 = 1365.2l^{-1.889} 
\]  
(10)

\[
F_1 = 1693.5l^{-1.876} 
\]  
(11)

**Figure 3.** Graphs of the dependencies of the first natural frequencies on lengths for pipeline sections with diameters of 32, 48, 70, 114, 168, 219 mm and their regression models
4. When the length of a pipeline section is shortened, the coefficient of determination of the regression equation describing the dependence of the first frequency of natural oscillations on the diameter tends towards unity. This means that the shorter the pipeline section, the better the regression model describes the experimental values.

5. The coefficient of determination of the regression equation describing the dependence of the first natural frequency on the length, when the pipeline section is reduced, behaves randomly. Nevertheless, its significance for all the cases studied is close to unity.

A linear multiple regression model was also considered in which the variables (length \(l\), diameter \(d\), and wall thickness \(\delta\) of the pipeline section) had a first degree. It does not qualitatively describe the experimental data obtained. It was concluded that the functional dependence under investigation is described by a nonlinear function.

Therefore, we believe that the regression function is a power-law model. This model refers to models that are non-linear in their parameters, where the linear least-squares method cannot be applied directly.

Since MS Excel tools allow only linear multiple regression to be performed, it was necessary to select an appropriate model conversion to bring it into a linear form. For a power-law model, this transformation is the logarithm of both parts of the model.

After analyzing the results of multiple regression analysis, we can draw the following conclusions:

1. The functional relationship between the value of the first natural frequency and the length, diameter, and wall thickness of the pipeline section is nonlinear (power law).

2. The regression model of the dependence of the first frequency of natural oscillations on two parameters (the length and diameter of the pipeline section) has the form:

\[
F_1 = 80.592 \cdot l^{1.688} \cdot d^{0.468} \cdot \phi_r \left( \frac{\rho}{\ell} \right) = (2\pi)^{2/3} \exp \left[ i k \cdot r \right]
\]  
(12)

The coefficient of determination in this case is \(R^2 = 0.879\).

3. The regression model of the dependence of the first frequency of natural oscillations on three parameters (the length, diameter, and wall thickness of the pipeline section) has the form:

\[
F_1 = 27.569 \cdot l^{1.658} \cdot d^{1.093} \cdot \delta^{-1.25}
\]  
(13)

The coefficient of determination in this case is \(R^2 = 0.893\).

4. The value of the coefficient of determination (the quality of the correspondence of the regression model to the experimental data) is the higher when the number of factor attributes is greater.

4. Conclusions

A method that allows excluding resonant phenomena in the operation of hydraulic systems of residential buildings using modal analysis in the ANSYS Workbench software package is proposed. It consists in determining the first critical frequency of natural oscillations of the pipeline for its further extraction beyond the region of forced frequencies by other methods.

Modal analysis of straight sections of the pipeline system filled with water, length 1.0; 1.5; 2.0; 3.0; 4.0; 5.0; 6.0 and diameters of 15 \(\times\) 1.0; 15 \(\times\) 1.2; 15 \(\times\) 1.4; 15 \(\times\) 1.5; 15 \(\times\) 1.6; 20 \(\times\) 2.0; 25 \(\times\) 2.0; 32 \(\times\) 2.8; 40 \(\times\) 3.0; 48 \(\times\) 3.0; 60 \(\times\) 3.8; 70 \(\times\) 4.0; 102 \(\times\) 5.0; 114 \(\times\) 5.0; 140 \(\times\) 5.0; 168 \(\times\) 5.0; 180 \(\times\) 5.0; 219 \(\times\) 6.0 mm in the software package ANSYS Workbench was conducted.

A paired regression analysis was performed for two cases: determining the dependence of the value of the first natural oscillation frequency on the diameter of the pipeline section and on the length of the pipeline section.

It is revealed that the regression equation describing the dependence of the first frequency of natural oscillations on the diameter of a pipeline section has the form of a sixth-order polynomial
function. The regression model of the dependence of the first frequencies of natural oscillations on diameters for pipeline sections with a length of 1.5, 3.0; 6.0 m is determined.

It was also revealed that the regression equation describing the dependence of the first frequency of natural oscillations on the length of the pipeline section has the form of a power function. The regression model of the dependence of the first frequencies of natural oscillations on the lengths for pipeline sections with diameters of 32, 48, 70, 114, 168, 219 mm is determined.

It is established that when the length of the pipeline section is shortened, the coefficient of determination of the regression equation describing the dependence of the first natural frequency on the diameter tends to unity.

Multiple regression analysis was performed and regression equations describing the functional relationship between the first frequency of natural oscillations and the length, diameter, wall thickness of the pipeline section were obtained. It is established that the functional relationship between the value of the first natural frequency and the geometric parameters (length, diameter, wall thickness) of the pipeline section is nonlinear (power law). The regression model of the dependence of the first frequency of natural oscillations on the two parameters (length and diameter of the pipeline section) is determined.

A regression model of the dependence of the first frequency of natural oscillations on three parameters (length, diameter and wall thickness of the pipeline section) is determined.

It is revealed that the value of the coefficient of determination (the quality of the regression model's correspondence to the experimental data) is higher the more the number of factor attributes.

Preliminary modal analysis becomes very important in the modeling of vibrations and transient processes in hydraulic system designs, since its main purpose is to predict and eliminate the occurrence of possible resonance regimes in them.

The frequency of the natural oscillations of the piping system designs obtained as a result of the modal analysis should be considered throughout the calculated frequency spectrum (and not only within the first critical frequency), since noise and vibration normalization is also performed in the frequency spectrum.

If the calculated natural frequencies are located in the operating range of the existing external loads, then there are dangerous resonant oscillations and the design will not satisfy the requirements for vibration strength. Then it is changed in such a way as to output the frequencies of natural oscillations beyond the range of forced frequencies of equipment of hydraulic systems.

The evaluation of the stress-strain state of the structure under the forced oscillation variables and the verification of the resonance regimes are performed with harmonic analysis, which is the next stage of the complete vibration study, and hence the safety of the engineering systems.

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