# Vibration Reliability of the Turbine Unit's Housing Considering Random Imperfections

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**Abstract.** The solution to the problem of the power turbines vibration reliability at failures arising as a result of resonant frequency hit in the operating range of a rotor considering the randomness of the support rigidity change on the foundation is considered. The study finds a complex machine-building object - the steam turbine housing on the foundation. The subject of the study is the failure as a result of vibration resonance in the operating frequency range. The reason for failures can be various design and technological imperfections. They can be divided into two groups: imperfections resulting from design and creation, and on the other hand - deviations from the design parameters as a result of the long-time operation. A special factor in the occurrence of various imperfections (deviations) is the time over which the probability of trouble-free operation decreases. To solve the problem, the methods of oscillation theory, reliability, and the widely used finite element method are used. Based on experimental data on the accumulation of rigidity imperfections on the foundation, the series of calculations of natural frequencies and forms, which are once again compared with experimental data, is carried out. The obtained results determined the probability of failures in the operating frequency range from the most dangerous resonances.

**Keywords:** Industrial growth · Steam turbine · Stiffness · Fatigue failures · Eigenvalue · Reliability · Energy efficiency

## 1 Introduction

The actual power unit of the power plant is a complex system of turbines and a generator connected by a standard rotor and foundation [1, 2]. In addition to these elements, there are other essential systems and units, but they not connected by a single foundation and are partially or entirely located in other workshops [3]. Typically, a single steam turbine system includes high (HP) and medium (MP) pressure cylinders, several low-pressure cylinders (LP), the generator, and the generator exciter [4]. The most pliable are the outriggers of the low-pressure rotor bearing, structurally made in one piece with the LP housing, which rests on the foundation through the plate balcony [5, 6]. Therefore, all

the LP housing structural elements are involved in reinforcing the bearings of the rotor bearings. This fundamentally distinguishes the fastening system of the rotor LP from the rotors HP, MP, and generator, whose bearing supports rest directly on the foundation. This approach is not generally accepted but is implemented in hundreds of actually created energy blocks [3, 7]. Many of these units are still in operation.

## 2   Literature Review

The authors have previously conducted numerical studies of various models of dynamic characteristics of the turbine-generator-foundation system elements and similar systems in general [8, 9]. Multiple approaches to modeling the turbine-generator-foundation system and comparing the efficiency of their application are described in [8]. The features of assessing the reliability of complex systems are described in [9]. The results of field tests [10, 11] allowed us to propose the following model of the turbine unit: LP, which is a complex system of shells, plates, and rods; foundation in the form of the system of plates and rods; other equipment [12, 13] is modeled in the form of concentrated masses.

When designing the foundation for turbines, from the very beginning, there is possible random scatter in the modulus of elasticity of concrete, associated with the manufacturing technology [14–16], which was higher at thermal power plants and nuclear power plants in the last century in the missing coalition [3, 10]. Recently, due to the depletion of the resources of most power plants in Europe, the task of modernizing existing power plants and using renewable energy [17, 18] has become urgent [18, 19]. It is economically advantageous to carry out a partial replacement of equipment, for example, leaving the old foundation to install a new turbine and generator. Therefore, considering the statistical variance of the characteristics of the stiffness of the resistance is an important problem since during the service life, there are temporary changes in the structure of concrete [3, 20]. This requires consideration of the rigidity of the LP body support as a random variable.

## 3   Research Methodology

We will use the solution to the reliability problem according to the following method: (1) creation of the mathematical model; (2) construction of geometric and computational models; (3) conducting a series of calculations of natural frequencies and forms of the system; (4) verification of the obtained intermediate results reliability; (5) obtaining reliability characteristics; (6) analysis of the obtained results.

We will use well-known approaches to the theory of oscillations, reliability, and the finite element method for mathematical modeling.

### 3.1   Mathematical Model for the Analysis of Natural Frequencies and Forms

The simple-element problem statement of the system natural frequencies has the form [8, 21]:

$$\left(\mathbf{K} - p_i^2 \mathbf{M}\right)\mathbf{V}_i = 0, i = 1 \div n, \tag{1}$$

where $\mathbf{K}$, $\mathbf{M}$ are the matrices of stiffness and mass, respectively, $p_i^2$ is the natural frequency for $\mathbf{V}_i$ natural form.

The method of iterations in subspace was used to determine the natural frequencies and forms.

## 3.2  Mathematical Model for Reliability Analysis

When solving the reliability problem, it is assumed that the rigidity of the body support on the foundation $\mathbf{C}$ is a random variable whose probability density $f(\mathbf{C})$ obeys the normal law with known parameters: $m_C$ is the average (nominal) value; $\delta_C^2$ is the variance. The maximum limit value $\mathbf{C}$ corresponds to a rigid support. Since the stiffness parameters of the system under study are random [22, 23], the natural frequency spectrum $\omega_i$ ($i = 1, ..., n$) will also be random. It is assumed [9] that in the small neighborhood of the nominal values of the natural frequencies $P_i(m_C)$, as a function of the stiffness $\mathbf{C}$, can be approximated by the Taylor series while preserving only the linear terms:

$$\omega_i(\mathbf{C}) = \omega_i(m_c) + (\mathbf{C} - m_c)\frac{d\omega_i}{d\mathbf{C}}\bigg|_{C=m_c}, \ (i = 1, ..., n). \tag{2}$$

In this case, the relationship between $\omega_i$ and $\mathbf{C}$ will be linear and the probability densities of the natural frequencies $f_i(\omega_i)$ will obey the normal law with mathematical expectation $m_{\omega_i}$ and variance $\delta_{\omega_i}^2$, which according to the Eq. (2) are determined from the relations:

$$m_{\omega_i} = \omega_i(m_C); \ \delta_{\omega_i}^2 = \left[\frac{dP_i}{d\mathbf{C}}\bigg|_{\mathbf{C}=m_c}\right]^2 \delta_C^2 \tag{3}$$

The derivative $dP_i/d\mathbf{C}$ is determined using finite-difference equations, the central differences were used in this paper.

The vibration reliability of the system [24–26] when considering failures that occur as a result of the natural frequencies in the operating range $[\omega_n, \omega_k]$, can be estimated by the failure probability $Q_i$ ($Q = \Sigma \, Q_i$), which represents the probability of the natural frequency $\omega_i(i = 1, ..., n)$ in set operating range:

$$Q_i = P(\omega_H \le \omega_i \le \omega_B) = \int_{\omega_H}^{\omega_B} f(\omega_i)d\omega_i \tag{4}$$

The final reliability value will be assessed by its integrated indicator - the availability factor $Kg$.

$$K_g = \frac{t}{t + t} \tag{5}$$

The availability factor $Kg$ (the probability of an operable state of the system at an arbitrary moment in time) is the ratio of the time of good operation $t_{CP}$ (without failures) to the sum of the times of good operation and forced downtime of the object ($t_{CP} + t_B$) or their mathematical expectations.

### 3.3   Construction of Geometric and Computational Models

Based on the drawings of an actual steam turbine, the basis of the geometric model was created. Then, using the finite element method, a computational model of the system was created. Figure 1 shows the symmetrical part of the lower half of the steam turbine K-325-25,3 housing for 1, 2, and 3 streams.
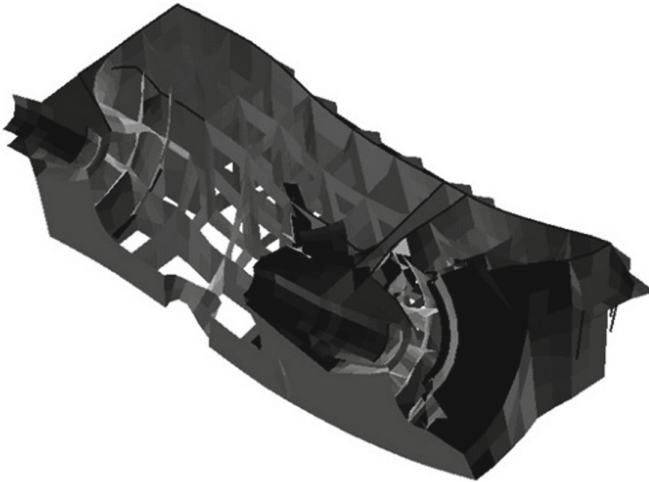


**Fig. 1.**   Calculation model. Forms of natural oscillations 8.

Accounting for the stiffness of only the lower half of the LP housing simplifies the calculation scheme. The system of masses considers the upper part. The plane of symmetry passes through the rotor axis. The lower parts of the LP of all streams are made in a single body, so they have a standard support balcony and are installed in one cell of the frame foundation. In addition, a feature of this design is a single rotor MP and LP 1st flow, which requires modeling of the LP housing as a shell and articulation with the LP housing into a single model. This version of the design of the LP is used for all turbines of the K-320-240 type, which were installed at many power plants in Eastern Europe and Asia in the 60-80s of the last century [27, 28]. Almost half of them have already exhausted their project resources. The latest modification of this series is the turbine K-325-25,3. It has the same dimensions but more power and efficiency.

The computational model (Fig. 1) has 3325 finite elements, 3186 nodes, and 19062 degrees of freedom. Quasi-shell finite elements in the form of a linear combination of plates for bending and flat stress were used for modeling. The LP building lies freely on the foundation. The support on the foundation was modeled by a system of stiffnesses attached to each particular unit of the supporting balcony. The reliability of the frequency analysis results is based on a comparison with another model, which has 24458 degrees of freedom. The average error in the values of natural frequencies is 6%.

## 4 Results

### 4.1 Calculations of Natural Frequencies and Forms of the System

Numerical calculations of natural frequencies and forms of oscillations are performed when varying the value of the stiffness of the foundation in the range from one rigid fastening to $C = 1 \cdot 10^7$ N/m$^2$. It is known from experimental data that the stiffness of foundation individual elements can vary significantly [29, 30]. This intensified, especially with the transition from monolithic foundations to prefabricated ones. Analysis of experimental data showed a scatter of stiffness up to 50% for one foundation structure and several times for foundation structures of monolithic and prefabricated types. A wide range is chosen to vary the foundation stiffness based on this. The calculation results are shown in Table 1.

From Table 1, it is seen that the whole spectrum of frequencies, depending on the stiffness of the support, can be divided into two parts: sensitive frequencies and insensitive. The values of the latter do not depend on the support rigidity. Some deviations of these frequencies are possible (P11, P4), but they are minor and related to their proximity at a given stiffness of moving frequencies. Analysis of the oscillation's forms showed that these frequencies belong to the "local", i.e., their forms are determined by the oscillations of individual structural elements: the housing walls, guide flows, etc. These frequencies cannot be the cause of failure when changing the stiffness characteristics of the foundation, and,, therefore can be excluded from the spectrum in the reliability analysis. Analysis of the oscillations forms of sensitive frequencies showed that they belong to the "global", i.e., their forms are determined by the oscillations of most structures. It is seen in Figs. 1 and 2 shows the type of eigenforms for 8 and 13 eigenfrequencies.

Comparison of the obtained natural frequency values with the experimental values (Table 1) shows a good correlation, indicating the obtained results' reliability. The limited experimental data is associated with the experiment method, where the measurements were performed discretely and in the range of 30–52 Hz. This is due to the high cost of experiments and the inadmissibility of measurements near the resonance.

Figure 3 shows a graph of the dependence of the values of "global" natural frequencies on the stiffness of the support, which shows that the frequency P8 takes values in the operating range (48–52 Hz), and the frequency P13 can get into it. Therefore, these factors will have the most substantial impact on the structure reliability in the studied model of failure.

### 4.2 Calculations of Reliability Indicators

Table 2 shows the values of the failure probability $Q_i$, mathematical expectations $m_{\omega_i}$, variance $\delta_{\omega_i}$ and the frequency gradient $\frac{d\omega_i}{dC}$ for the "global" natural frequencies of the LP when varying the values of the stiffness of the support in the range $1 \cdot 10^7..4 \cdot 10^8$ N/m$^2$. The operating frequency range was taken equal to 48–52 Hz.

There is a high failure probability of the frequency P8 in the operating range (Table 2). The natural form of this frequency (Fig. 2) is characterized by the joint deformation of

**Table 1.** The natural frequencies (Hz) of the LP when varying the stiffness of the support.

| № | The value of the stiffness of the support ($10^7$ N/m$^2$) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Experimental | Rigid | 1000 | 100 | 70 | 40 | 20 | 10 | 7 | 5 | 3 | 1 |
| 1 | – | 28 | 27.9 | 26.8 | 26.2 | 24.8 | 22.1 | 18.5 | 16.5 | 14.6 | 11.9 | 7.2 |
| 2 | 31 | 32.0 | 31.5 | 29.1 | 28.7 | 28.3 | 28.0 | 28.7 | 29 | 27.9 | 27.8 | 27.7 |
| 3 | 42 | 41.3 | 40.9 | 38.9 | 38.3 | 36.8 | 33.7 | 27.4 | 24.7 | 21.6 | 17.3 | 10.4 |
| 4 | | 45.3 | 45.4 | 45.4 | 45.4 | 45.3 | 45.4 | 45.3 | 45.3 | 45.3 | 45.3 | 45.3 |
| 5 | | 45.4 | 45.4 | 45.4 | 45.4 | 45.4 | 45.4 | 45.3 | 45.4 | 45.4 | 45.4 | 45.4 |
| 6 | | 45.6 | 45.6 | 45.6 | 45.6 | 45.6 | 45.6 | 45.6 | 45.6 | 45.6 | 45.6 | 45.6 |
| 7 | | 55.2 | 55.2 | 55.2 | 55.2 | 55.3 | 55.2 | 55.2 | 55.3 | 55.3 | 55.3 | 55.2 |
| 8 | – | 56.5 | 56.5 | 56.1 | 55.8 | 54.6 | 50.3 | 45.7 | 44.0 | 43.0 | 42.0 | 41 |
| 9 | – | 60.5 | 60.4 | 59.5 | 59.1 | 58.2 | 57.4 | 57.2 | 57.2 | 57.1 | 57 | 56.7 |
| 10 | | 61.7 | 61.7 | 61.7 | 61.6 | 61.6 | 62 | 61.5 | 61.5 | 61.5 | 61.5 | 61.5 |
| 11 | | 62.6 | 62.5 | 62.2 | 62.1 | 62.1 | 61.6 | 61.9 | 61.7 | 62.2 | 62 | 62 |
| 12 | | 66.7 | 66.7 | 66.7 | 66.8 | 66.7 | 66.6 | 66.7 | 66.6 | 66.6 | 66.6 | 66.5 |
| 13 | – | 68.5 | 68.5 | 67.7 | 66.5 | 63.2 | 58.7 | 55.6 | 54.2 | 53.3 | 52.2 | 51.0 |



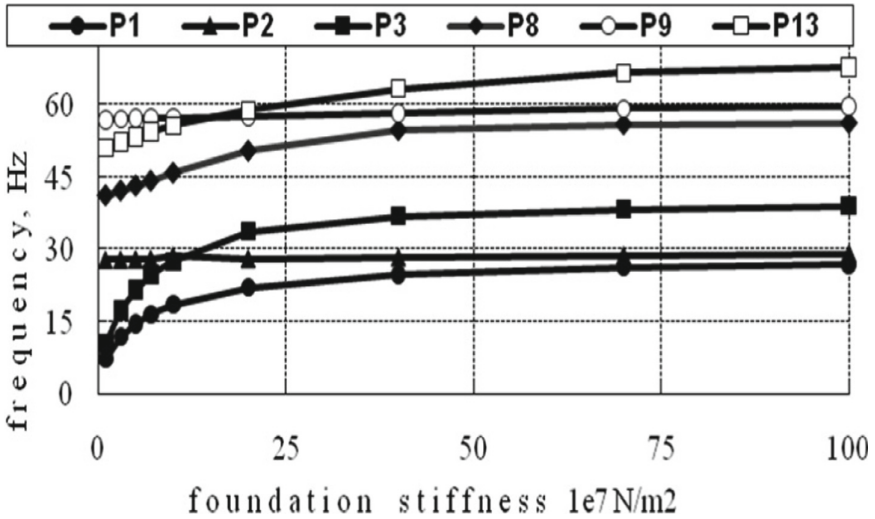**Fig. 2.** Forms of natural oscillations 13.

**Fig. 3.** Effect of natural frequencies on the uniform stiffness of the foundation.

**Table 2.** Characteristics of LP vibration reliability.

| Eigenvalues | $Q_i$ | $m_{\omega i}$ | $\delta_{\omega i}$ | $\frac{d\omega_i}{dC}$ |
|---|---|---|---|---|
| P1 | 3.52E−19 | 22.06 | 2.9230 | 4.497E-8 |
| $P_2$ | 0.00 | 28.00 | 0.0950 | 1.461E-9 |
| $P_3$ | 5.574E−4 | 33.67 | 4.4066 | 6.779E-8 |
| $P_8$ | 0.6128 | 50.29 | 2.2683 | 3.490E-8 |
| $P_9$ | 0.00 | 57.44 | 0.2550 | 3.920E-9 |
| $P_{13}$ | 4.651E−4 | 58.71 | 2.0266 | 3.118E-8 |

bending and torsion of the structure as a whole, so to change the value of this frequency requires completion of the entire structure.

Summing up the probabilities of failures at different frequencies, we get the final value $Q = 0.6138$. Given that the park resource of steam turbines is 270 thousand hours, and the repair time is 1248–1560 h, we get the time of failure-free operation 104 274 h and availability factor (formula 5) $Kg = 0.987$.

## 5  Conclusions

Mathematical models for solving the problems of natural oscillations and the reliability of the turbine unit are formulated considering random imperfections. Geometric and computational models building are completed. A series of natural frequencies calculations and forms of the system, comparisons with experimental data are performed. The natural frequencies in the spectrum with high sensitivity to the rigidity of the foundation,

the forms of which are characterized by the global deformation of the whole system, are determined. Reliability characteristics are determined, which show a high probability of getting individual natural frequencies in the operating range. This can lead to accidents in the system under study. The uptime and availability factors have been calculated. The time of failure-free operation given in the study is slightly longer than the time recommended by factories of 70–100 thousand hours before repair. However, this time is determined by the wear of the flow path (blades, diaphragms), which is also affected by the vibration level. Therefore, the study results correlate well with long-term experimental studies of factories to manufacture steam turbines. Additional research is needed to determine effective measures to prevent system failure.

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