An estimation of mechanical stresses in the stator of the NB-514 motor of an electric locomotive

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Abstract. The aim of the research is to determine the causes of cracks in stators of traction electric motors of the NB-514 series. The application of mathematical modeling using the finite element method, which allows one to evaluate the mechanical stresses arising in the stator under the influence of thermal and vibration loads, is considered. The results of thermal modeling are presented for uneven heating of the electric motor frame to temperatures typical for the hourly operation of a traction motor. The results of vibration modeling, including the study of natural vibration modes and frequencies, are also presented. Based on the results of the studies, it was concluded that the cause of the formation of cracks in the area of ventilation hatches is a complex of cyclically repeating temperature and vibration effects, creating points of mechanical stress with a large value in the area of crack formation. Vulnerabilities in the design of the electric motor frame have been identified. Options have been proposed for improving the design of the ventilation hatches of the frame, allowing reducing mechanical stresses with a constant area of the ventilation and inspection hatches.

1 Introduction

Reliability, operability and safety of the transportation process are the most important in railway transport. Particular attention should be paid to the technical condition of the most important components of the rolling stock, promptly identifying the reasons for its deterioration and further destruction. One of these components is the traction motor.

Currently, AC electric locomotives of the VL85 and 2,3,4ES5K series are equipped with NB-514 traction motors. These traction electric motors are the most loaded units of electric locomotives from the point of view of the complex influence of thermal, mechanical, electrical and climatic factors. Despite regularly carried out technological measures in the manufacture and repair of locomotives, the damage rate of traction motors during operation remains quite high. The main attention is paid to thermal processes in the windings of a traction motor [1-10], but mechanical stresses arising in the frame due to heating and vibration are practically not considered.

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There is a significant problem of crack formation in the cores of NB-514 traction motors during operation. The formation of cracks occurs in the same place, near the ventilation hatches on the side of the collector-brush assembly (Figure 1). The presence of cracks leads to accelerated engine failure and the placement of the locomotive for unscheduled repairs. This entails significant material and time costs.

The aim of this work is to study the possible causes of crack formation in the cores of NB-514 traction motors. This research is divided into the following tasks:

- studying of thermal processes occurring in the frame of the traction motor;
- studying of the natural shapes and frequencies of the traction motor core;
- modeling the impact of vibration under the influence of external applied forces on the structure of the traction motor frame to determine vulnerable points and the magnitude of mechanical stresses.

To solve these problems, the finite element method was chosen. The finite element method makes it possible to divide regions of any shape into finite elements and, thus, makes it possible to calculate stress and strain fields in real parts, taking into account all their design features [11-13].

When using the finite element method, the stator model is divided into finite elements that fairly accurately describe the geometry of the structure. The curved region is approximated using rectilinear elements. The mesh spacing can be reduced in areas where the expected result may vary greatly, and increased in areas where the expected result is almost constant. And performing modal analysis during dynamic calculations to determine the forms and frequencies of natural vibrations allows one to determine the correctness of the design scheme using the first forms and compare the values of natural frequencies with regulatory requirements.

### 2 Thermal analysis of the current engine design

To carry out mathematical modeling, a simplified three-dimensional model of the core of the NB-514 traction motor was created (Figure 2) [14].
The previously calculated temperature values served as the load on the frame. The temperature loading diagram is presented in Figure 3. To carry out the calculation, the properties of steel grade 25L were specified for the model material. The fixation of the frame is standard, for support-axial suspension of the NB-514 electric motor according to the manual [15].

Below are the results of a thermal finite element analysis of the internal mechanical stresses of the electric motor frame. In the area where the excitation winding of the electric motor is located, the temperature is set at 180 °C, and 40 °C in the area of the ventilation hatches, which simulates the temperature of the ambient air cooling the motor. A temperature of 180 °C was selected as characteristic for the hourly operation mode of the traction motor in the area of its windings. The temperature model used is suitable for solving this problem, which analyzes the mechanical stresses occurring in the area between the engine ventilation hatches away from the pole windings. Obviously, at a lower temperature near the windings, the mechanical stresses will also be proportionally less than those calculated in the paper. The results of the thermal calculation are presented in Figure 4.
To determine the mechanical stresses, the results of thermal calculations obtained earlier when heating the core were used. An analysis was carried out of the obtained results of calculating mechanical stresses, presented in Figure 5. From Figure 5 it can be seen that the most loaded sections of the model correspond to the places where cracks appear in the frames of traction electric motors during their operation (Figure 1).

Based on previously conducted thermal analysis studies, it can be noted that one of the reasons for the formation of cracks in the cores of traction electric motors is cyclically repeating temperature stresses, which arise, for example, in the hourly mode of an electric locomotive traction motor both in traction mode and in regenerative braking mode. Such voltages are of particular importance for electric locomotives that constantly operate in mountainous mountain pass areas, for example, as electric push locomotives.

### 3 Vibration analysis of the current engine design

One of the supposed factors for the formation of cracks in the area of ventilation hatches, in addition to thermal loads, is vibration emanating from the electric motor itself (rotor rotation, gearbox) and from the railway track. A vibration modal analysis was carried out.
Based on the results of the modal analysis, the following natural frequencies were identified: 74 Hz, 125 Hz, 225 Hz, 284 Hz, 308 Hz, 365 Hz, 386 Hz, 416 Hz, 471 Hz and 517 Hz. For a detailed analysis within the framework of this work, a frequency of 365 Hz and the corresponding oscillation shape of the electric motor frame structure at this frequency were selected. Based on the analysis of the vibration shape, it is obvious that this vibration shape will create mechanical stresses in the area of crack formation. The results of the modal analysis are presented in Figure 6 for a frequency of 365 Hz (maximum mechanical stress in the area of the ventilation hatches).

![Fig. 6. Natural mode of oscillation of the core of the NB-514 traction motor at a frequency of 365 Hz.](image)

Also, this frequency is slightly highlighted in broadband oscillations that arise as a result of the interaction of the wheel and rails both at the joint sections of the track and in small radius curves [15].

To determine the magnitude of mechanical stresses, the frame of the traction motor should be loaded at the points obtained from the previous analysis. From the side of the wheelset axis, alternating distributed forces of 40 kN with a frequency of 365 Hz were applied (and for modified structures - at the frequency of the mode at which oscillations with the main stresses between the windows occur).

This value of the applied force was selected based on the mass of the electric motor frame, for an approximate assessment of the magnitude of the mechanical stresses arising in the areas of the ventilation hatches. It should be noted that the magnitude of these forces is conditional and is used to analyze the additional mechanical stresses that arise, superimposed on the low-frequency stresses arising due to the temperature gradient, while temperature stresses cause low-cycle fatigue of the engine core metal, and vibration stresses cause simultaneously occurring high-cycle fatigue [16-19].

Figure 7 shows the results of the analysis to determine the possible values of mechanical stress. It is clear from the figure that when exposed to alternating forces with an excited frequency of 365 Hz and a value of 40 kN from the side of the wheel pair axis, they generate mechanical stresses in the area of the ventilation hatches, on the periphery - in the corners, and have the following maximum values: 170 MPa and 74 MPa, for the specified calculation parameters.

![Fig. 7. Mechanical stresses under vibration influence (load value 40 kN at a frequency of 365 Hz).](image)
Thus, these same corner places of ventilation hatches are also concentrators of mechanical stresses that arise during vibration. And the significance of vibrations of the traction motor frame at this frequency is confirmed by the data obtained in this work [15], in which a resonance is visible at a frequency of about 360 Hz when vibrations are excited by a harmonic of the gear frequency.

4 Traction motor stator geometry correction

To reduce the degree of mechanical stress, it is necessary to remove stress concentrators from the structure; in this case, the concentrators are the corners of ventilation hatches. Next, the authors propose options for modifying the ventilation hatches of the electric motor (Figure 8), while the area of the hatches is comparable to the original one.

Fig. 8. Proposed solutions for ventilation hatches in the design of the frame of the NB-514 traction motor: a – oval; b – truncated trapezoid; c – combined version.

Below will be presented the results of thermal and vibration analysis of each proposed modification option. The results of thermal calculations for a structure with oval hatches are presented in Figure 9.

Fig. 9. Results of calculating mechanical stresses of a modified structure (oval hatches) during thermal analysis due to the temperature gradient.
The results of the modal analysis for windows with an oval shape are presented in Figure 10 for a frequency of 394 Hz (maximum mechanical stresses in the area of ventilation hatches at this mode).

![Figure 10](image10.png)

**Fig. 10.** Natural vibration mode of the core of the NB-514 traction motor at a frequency of 394 Hz.

The results under a vibration load of 40 kN at a frequency of 394 Hz are presented in Figure 11 (oval shape of hatches).

The results of thermal calculations for a structure with hatches in the form of a truncated trapezoid are presented in Figure 12.

The results of the modal analysis with the shape of the hatches in the form of a truncated trapezoid are presented in Figure 13 for a frequency of 397 Hz (maximum mechanical stresses in the area of the ventilation hatches at this mode).

![Figure 11](image11.png)

**Fig. 11.** Results of calculation of mechanical stresses (oval shape of hatches) during vibration analysis at a frequency of 394 Hz (load value 40 kN).

![Figure 12](image12.png)

**Fig. 12.** Results of calculating mechanical stresses of a modified structure (the shape of hatches in the form of a truncated trapezoid) during thermal analysis due to the temperature gradient.
Fig. 13. Natural vibration shape of the core of the NB-514 traction motor at a frequency of 397 Hz.

The results under a vibration load of 40 kN at a frequency of 397 Hz are presented in Figure 14 (truncated trapezoid shape).

The results of thermal calculations for the design of combined hatches are presented in Figure 15.

The results of the modal analysis with the shape of the hatches in the form of a truncated trapezoid are presented in Figure 16 for a frequency of 392 Hz (maximum mechanical stresses in the area of the ventilation hatches at this mode).

Fig. 14. Results of calculation of mechanical stresses (shape of hatches in the form of a truncated trapezoid) during vibration analysis at a frequency of 397 Hz (load value 40 kN).

Fig. 15. Results of calculation of mechanical stresses of a modified design (shape of hatches of a combined design) during thermal analysis due to the temperature gradient.
Fig. 16. Natural vibration modes of the core of the NB-514 traction motor at a frequency of 392 Hz.

The results under a vibration load of 40 kN at a frequency of 392 Hz are presented in Figure 17 (shape of combined hatches).

From the above Figures 9-17 it is clear that changing the geometry of the ventilation hatches of the frame reduces the magnitude of the maximum mechanical stresses caused by thermal and vibration loads in the area of the ventilation hatches by almost half. In this case, the points of maximum stress move inward from the outer surface of the frame.

The results of mechanical stress values with different options for ventilation hatches are shown in Table 1.

Fig. 17. Results of calculation of mechanical stresses of a modified structure during vibration analysis at a frequency of 392 Hz (load value 40 kN).

**Table 1.** Mechanical stresses in the engine frame with different options for ventilation hatches.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Typical frame design</th>
<th>Modification of the design with oval ventilation hatches</th>
<th>Modification of the design with ventilation hatches in the form of a truncated trapezoid</th>
<th>Modification of the design with ventilation hatches of a combined design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum mechanical stress during uneven heating, MPa</td>
<td>106</td>
<td>72.8</td>
<td>77.3</td>
<td>83.9</td>
</tr>
<tr>
<td>Natural oscillation mode frequency, Hz</td>
<td>365</td>
<td>394</td>
<td>397</td>
<td>392</td>
</tr>
<tr>
<td>Maximum mechanical stress, MPa (vibration load 40 kN at mode frequency)</td>
<td>170</td>
<td>51</td>
<td>83</td>
<td>64</td>
</tr>
</tbody>
</table>
5 Conclusion

This paper presents the results of a study of thermal and vibration processes from the point of view of estimation of the mechanical stresses arising in the frame of the NB-514 series traction motor in the area of the inspection and ventilation hatches, using a software package for solving problems using the finite element method.

The article states that there are mechanical stress concentrators in the design - rather sharp corners of ventilation hatches. Uneven heating combined with vibration load creates conditions for the occurrence of cracks.

The natural mode of vibration of the core is determined, located at a frequency of 365 Hz, at which the structure of the core performs such modes of vibration with the highest stress concentration in the area of the ventilation hatches.

The cracks developing in the motor frame correspond to the points of maximum stress obtained from the analysis of temperature stresses and stresses from the results of modal analysis with subsequent analysis of the mechanical stresses of the frame of the NB-514 traction motor. Under the considered temperature and vibration loads, cyclic fatigue of the material occurs in places of stress concentrations, which leads to crack formation and, as a consequence, the need to send the electric locomotive for unscheduled repairs.

The modified design of the ventilation hatches of the traction motor frame is characterized by a reduction in mechanical stress. In the case of mechanical stresses caused by uneven heating of the frame, the following results were obtained: a modified design with oval hatches and hatches in the form of a truncated trapezoid reduces mechanical stresses by 1.5 times; modification with hatches of a combined design does not significantly reduce mechanical stress.

Significant reductions in mechanical stresses are observed when analyzing a vibration-loaded state: modification of the design with oval hatches made it possible to reduce mechanical stresses by 3.5 times; modification with hatches in the form of a truncated trapezoid reduces mechanical stress by 2 times; modification with combined hatches reduces mechanical stress by 2.5 times.

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