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UDC 621.33
DOI: 10.15587/1729-4061.2020.192468

DEVELOPMENT OF DYNAMIC INTEGRAL EVALUATION METHOD OF TECHNICAL STATE OF ONE-SECTION ELECTRIC LOCOMOTIVE BODY

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В теперішній час одна з основних проблем, що виникає під час тривалої експлуатації односекційних електровозів, пов'язана із необхідністю підтримання їх справного технічного стану. При цьому нерідко визначальним аспектом є оперативне виявлення наявних дефектів і пошкоджень основних несучих конструктивних елементів кузовів машин, а також недопущення їх розвитку в більш серйозні конструктивні відхилення.

Метою проведених досліджень є розробка спеціалізованого методу, що дозволяє виявити виникаючі в процесі експлуатації односекційних електровозів дефекти їх основних несучих конструктивних елементів кузовів на ранніх стадіях виникнення й розвитку. Даний метод динамічної інтегральної оцінки оснований на аналізі парційного динамічного спектру конструкції електровозу. За величиною відхилень від спектру по відношенню до теоретичного, отриманого на основі моделювання методом скінчених елементів, є можливим встановити приблизний характер і місце розташування наявного пошкодження, особливо скритого типу.

Отриманий в ході досліджень частотний спектр основних несучих конструктивних елементів кузовів односекційних електровозів є досить щільним і знаходиться в діапазоні частот до 20 Гц. Наявність пошкоджень знижує його значення, причому для найбільш розповсюджених в практиці експлуатації типів дефектів подібне зниження становить 25–30 %.

Ефективність практичного застосування метода динамічної інтегральної оцінки проілюстрована на прикладі машини ДСЗ-008. Метод дозволив виявити скрите пошкодження одного із елементів несучого каркасу передньої поверхні кабіни, не встановлене при стандартній процедурі технічного обслуговування машини. Застосування методу динамічної інтегральної оцінки технічного стану для електровозів є доволі універсальним та може бути рекомендовано також і для інших одиниць залізничного рухомого складу. В практиці впровадження подібного підходу дозволить ефективно попереджувати розвиток аварійних ситуацій

Ключові слова: односекційний електровоз, технічне обслуговування, метод динамічної інтегральної оцінки, технічний стан

Received date 30.09.2019
Accepted date 09.01.2020
Published date 24.02.2020

1. Introduction

At present, a whole fleet of one-section electric locomotives of various types and manufacturers is widely used on railways. They were produced in bulk in the 20th century and therefore have a fairly significant life. Most machines of this type are designed for standard-gauge railways (1,524/1,520 mm). The most structurally successful machines of world manufacturers are shown in Fig. 1. Their operation continues at the present time.

In contrast to multi-section machines, one-section machines are characterized by simpler design, better maintainability, smaller dimensions, but, as a result, lower traction. However, in modern world conditions this is quite justified, especially for small volumes of freight transportation or servicing small passenger flows. In addition, one-section electric locomotives have a much smaller destructive effect on the track superstructure, thereby reducing the cost of its periodic maintenance and repair. Therefore, the world's leading manufacturers continue to build such machines, taking into account operating experience (Fig. 2).

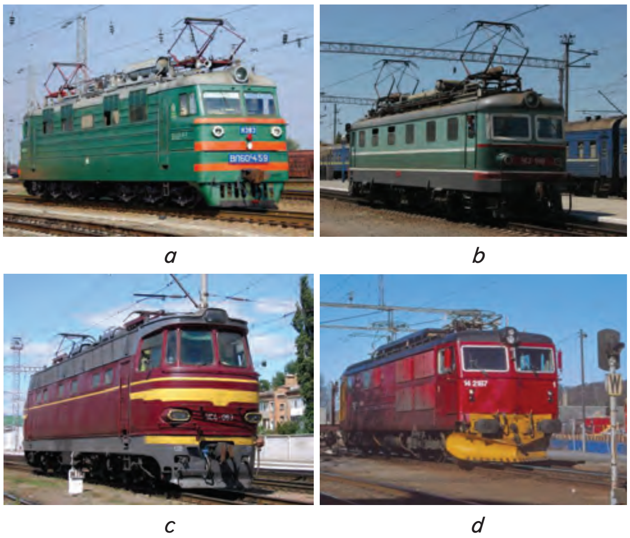

Fig. 1. Wholesale one-section electric locomotives produced in the 20th century: *a* – VL60 (Russia, 2618 units); *b* – ChS2 (Czech Republic, 942 units); *c* – ChS4 (Czech Republic, 230 units); *d* – NSB El14 (Norway, 31 units)

Fig. 2. Modern one-section electric locomotives: *a* – Vectron (Germany); *b* – Taurus Rh242 Hectorrail (Sweden); *c* – BKG2 (China); *d* – EP2 (Russia)

The main problem arising from the operation of the existing fleet of one-section electric locomotives is the need to maintain their good technical condition. This issue is especially relevant for machines of earlier production, the continuous operating period of which is already an average of 40–70 years. However, manufacturers of modern machines are also thinking about its solution.

The situation is that the equipment available in railway service companies is designed mainly for electric locomotives of previous years of manufacture. Therefore, it is of little use for new machines, which makes the problem of operational diagnostics of their technical condition quite relevant.

It should also be added that the continuous modernization of one-section electric locomotives of the new series, which is a necessary practice for finishing machines, leads to the emergence of new options of potential failures in their structural parts. Therefore, maintaining proper technical condition, primarily of bodies, is even more difficult and urgent problem in this case. In addition, it is not uncommon for parts necessary for repair and restoration work to be supplied by the manufacturer in limited quantities. This also complicates repair and diagnostic operations.

2. Literature review and problem statement

In [1], the results of studies of the current technical condition of the electric rolling stock are presented. It is shown that the main problematic aspect of maintaining good technical condition of one-section electric locomotives is the need for timely and accurate detection of defects and damages occurring in machine elements, primarily machine bodies. This is the cornerstone for maintaining the operable condition of the electric locomotive fleet and causes a rather high wear degree to date. The same work indicates possible solutions of such a problem, which, one way or another, are reduced to improving the quality of repair. This is achieved both by complicating the technological operations employed and using more advanced equipment.

In [2], it is shown that such a problem is more or less characteristic not only of electric locomotives, but also, for example, of traction units. At the same time, the solution proposed in this work, aimed at high-quality balancing of machines, turns out to be unacceptable for one-section electric locomotives due to the fundamental impossibility of implementation.

Also, methods of mathematical modeling of the process of repairing locomotives in general and electric locomotives in particular are being actively developed. So, the work [3] presents the concept of separation of the operation process and the repair process of machines by creating a special system of different types of depots – operational and repair, respectively. The disadvantage of this approach is the need for high material costs, first, directly for their creation, and second, for their further maintenance, which is difficult to justify economically.

The work [4] provides a model of the repair shop, which can be equipped with any depot. The focus is on optimization of the repair process, for which specialized intelligent computer systems are proposed [5]. In practice, this most often comes down to the use of special software packages [6], the cost of which is quite significant. Also, the availability of such software products in today's market is limited, and their quality leaves much to be desired. And more importantly, such packages do not allow monitoring the technical condition of machines. In some cases, locomotives are even proposed to be equipped with specialized diagnostic complexes that allow real-time monitoring of changes in a wide range of various traction and mobility characteristics [7].

Since a modern one-section electric locomotive is an extremely complex dynamic system with many partial degrees of mobility, it is recommended to use the finite element method (FEM) to identify them, as recommended in [8]. To date, it has a number of improvements compared to the classic approach, as emphasized in [9].

For its practical implementation, a number of different design and computing systems have been developed that allow performing, first of all, an analysis of static operation of machines on specially developed mathematical models. The most powerful and versatile among them is the ANSYS complex [10]. However, this complex is not convenient enough and cumbersome for solving many dynamic problems, including modal analysis, as revealed in [11].

The NASTRAN complex is considered easier to use. It has specialized «rigid» elements as part of the finite element database, the detailed application of which is presented in [12]. Using them, it is quite convenient to model the transmission of inertial loads during dynamic calculations, but they lead to «rigid noise» in model analysis.

Also, SolidWorks [13] is often used in machine-building practice, but its finite element base is devoid of rod elements. This seriously limits the use of this product in modeling, for example, electric locomotives, the design of which includes many small reinforcing stiffeners and reinforcing frame elements. A similar disadvantage is also present in the CosmosWorks complex [14]. It also has rather serious limitations on solving modal analysis problems.

Thus, at present, all the proposed scientific developments and applied approaches in the field of maintaining good technical condition of one-section electric locomotives in general and their bodies in particular are aimed at improving the repair process. At the same time, the problem of timely and accurate detection of defects and damages arising in the elements of such machines remains unaffected and has not yet been resolved. Therefore, it is advisable to conduct studies aimed at resolving this situation.

3. The aim and objectives of the study

The aim of the study is to develop a specialized method that allows identifying defects in the main bearing structural elements of electric locomotive bodies at the early stages of their occurrence and development. It is assumed that this method will be based on an analysis of the dynamic characteristics of the machine, as the most general indicator reflecting design features.

To achieve the aim, the following objectives are formulated:

– to theoretically determine the range of partial dynamic characteristics of the body of a one-section electric locomotive;

– to evaluate the effect of structural deviations on the resulting range of partial dynamic characteristics;

– to develop a method for dynamic integral evaluation of the technical condition of the main structural elements of the one-section electric locomotive body;

– to perform practical testing of the developed method.

4. Materials and methods for studying partial dynamic characteristics of one-section electric locomotive

To conduct these studies, the authors choose the SCAD for Windows software [15], developed in Ukraine. Features of its use for machine-building tasks were separately analyzed and described in [16]. On the basis of this complex, all the necessary dynamic calculations were carried out.

Since the FEM involves modeling of a specific physical object, a modern DS3 electric locomotive was chosen for research (Fig. 3). This choice was due to the fact that this machine is a fairly new development, which greatly simplifies the analysis of the technical condition of its structural elements compared to machines manufactured earlier.

Fig. 3. DS3 one-section electric locomotive

It should be noted separately that the tests of these machines have been carried out for quite a long time by the Branch Research Laboratory of the Dynamics and Strength of Rolling Stock of the Dnipro National University of Railway Transport (Ukraine). Their results were presented in a series of publications. So, static strength tests are reflected in [17]. The most important were dynamic strength tests, which allowed, among other things, to experimentally determine a number of dynamic characteristics of the electric locomotive. Their results are presented in [18], on the basis of which the design of the DS3 electric locomotive was partially upgraded, which should increase its operational reliability and durability.

5. Results of determination and study of partial dynamic characteristics of one-section electric locomotive body

5. 1. Range of partial dynamic characteristics

The developed mathematical model (finite element model) of the DS3 one-section electric locomotive is shown in Fig. 4, *a*. The model is a plate-rod system. The rods modeled both a number of bearing elements of the frame and body of the machine, as well as components of equipment on which concentrated masses are mounted (Fig. 4, *b*). Plate elements are of isoparametric type, and rod elements are of versatile rod type. In total, the model includes about 50,000 elements, as well as about 40,000 nodes, which results in approximately 250,000 degrees of freedom.

All numerical calculations were performed in a physically and geometrically linear formulation. This allowed for classical approaches to dynamic calculations.

To check the adequacy and validity of the developed mathematical model of the electric locomotive, as well as to determine the required degree of discretization of the finite element mesh, the results were compared with experimental data. As a basis, the data of static strength tests according to [17] were taken. Table 1 shows a comparison of these results according to the layout of sensors (Fig. 5).

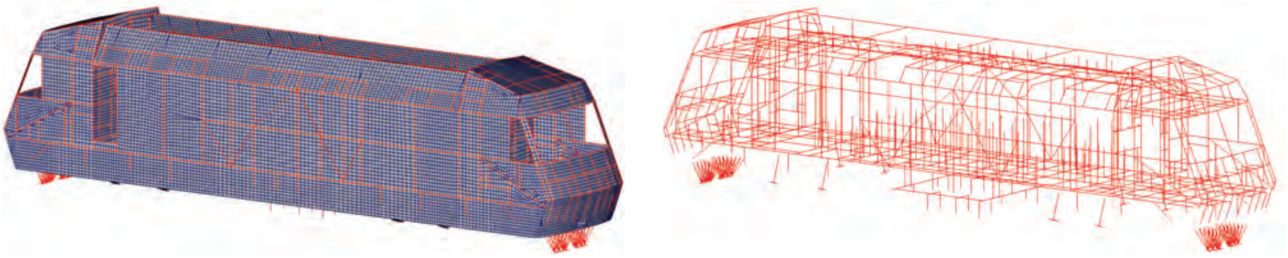

Fig. 4. Finite element model of the DS3 electric locomotive: *a* – appearance; *b* – rod frame

Table 1

Comparison of experimental and theoretical data on static operation of the DS3 electric locomotive

No.	Sensor	Stresses according to, MPa		Error, %
		experiment	FEM	
Body frame rails				
1	1X1	−185	−155÷−230	−16÷+24
2	1X2	−77	−67	−13
3	11X1	−116	−105÷−125	−9÷+8
4	11X2	−85	−76	−11
5	3X1	−157	−110÷−120	−30÷−24
6	12X1	−108	−100÷−120	−7÷+11
7	12X2	−69	−74	+7
8	8X1	−123	−130÷−135	+6÷+10
9	YP1	54	−25	−146
10	3Y	0	+9	–
11	4Y	−1	+16	–
12	5Y	+3	+16	–
13	5iY	+18	+16	−11
14	5X	−9	−6	–
15	5iX	−9	−7	–
16	6Y1	+11	+13	+18
17	6iY	−3	−6	–
18	7iX	−13	−9	−31
19	7iY	+10	+10	–
20	8iX	−18	−7	−61
21	8iY	+8	19	–
22	9X	−48	−35	−27
Buffer beam				
23	1Y	290	−225÷−240	−22÷−17
24	2Y	103	+100÷+115	−3÷+12
25	2iY	82	+100÷+110	+22÷+34
26	V2X	14	+15	+7
27	X	225	+150	−33
28	Y	99	+100÷+110	+1÷+11

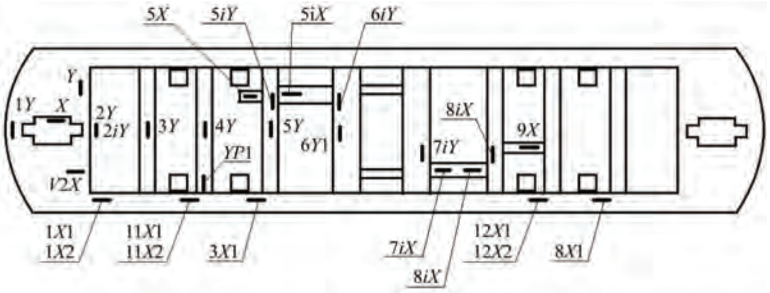

Fig. 5. Layout of control sensors on the bearing frame of the electric locomotive

In general, as can be seen from the data given in Table 1, the comparison of the results revealed a rather good level of agreement between the numerical and experimental data. The deviation averaged about 15 %. The only problematic place was the YP1 point (shown in Table 1 with a darker color), where the design stress was significantly different from the experimental one. During the analysis of the results, it was not possible to determine the reason for this deviation. It is most likely due to a failure of the sensor itself or its poor connection to the structural element during testing. Since the stress level was quite low (about 10 MPa) in a number of body frame rails, the error for these points was not calculated.

We also note that at one of the first stages of modeling the DS3 electric locomotive, the finite element model of only the frame of the machine with a part of its plating was constructed. However, when comparing the data from this model with the experimental data, the discrepancies were quite significant and reached 300 % at some points. Therefore, it was necessary to complete the model of the machine – the body with side plating, roof and entire system of internal bearing partitions.

Thus, one of the first intermediate conclusions of the research was the conclusion that the body of the electric locomotive has a significant impact on the stress-strain state of the entire machine and it must be considered together with the bearing frame.

The well-adjusted and tested finite element model of the electric locomotive was used to determine the dynamic characteristics of the machine. Table 2 shows the values of the natural frequency spectrum obtained from the results of dynamic tests of the electric locomotive according to [18].

As can be seen from the above results, the error for all major oscillation modes does not exceed 15 %. Also of note is the rather dense frequency spectrum characteristic of the DS3 one-section electric locomotive, especially for low frequencies.

Thus, it can be stated that in terms of determining natural dynamic characteristics, the developed finite element model of this machine is also quite reliable and correct. Therefore, it was used to study the partial modal spectrum of individual structural elements of the electric locomotive body. The natural frequencies obtained are presented in Table 3. For the most important bearing structural elements of the machine body, the obtained modes of natural oscillations are shown in Fig. 6. The mode itself is shown in green, and the initial position of the structural element in black.

In Fig. 6, for higher oscillation modes (*c*–*e* modes), there are nodal points on a number of the bearing structural elements of the body. In them, the oscillation amplitude is zero, so upon excitation of such modes, the strain gauges at these points will not allow obtaining data on the corresponding partial frequencies. This creates prerequisites for formulating recommendations on the correct placement of the strain gauge system in the future not in such oscillation nodes.

Table 2

Comparison of experimental and theoretical natural frequencies of the DS3 electric locomotive

No.	Oscillation mode	Natural frequency according to, Hz		Error, %
		experiment	FEM	
1	Swaying	0.62	0.69	+11.3
2	Rolling	0.68	0.76	+11.8
3	Heaving	0.72	0.81	+12.5
4	Hunting	0.83	0.84	+1.2
5	Bouncing	1.07	1.22	+14.1
6	Pitching	1.17	1.31	+12.0
7	Bending oscillations	10.43	10.02	–3.9

Table 3

Partial frequency spectrum of the main structural elements of the DS3 electric locomotive body

No.	Structural element	Frequency, Hz
1	Binding frame of the roof top	2.17
2	Bearing frame of the cab floor	6.98
3	Side rails of the roof bottom	7.32
4	Bearing frame of the cab front surface	9.94
5	Side rails of the body floor	10.21
6	Bearing frame of the cab rear wall	10.53
7	Cross rails of the roof bottom	11.49
8	Cross rails of the body floor	12.34
9	Side rails of the body side walls	14.88
10	Bearing frame of the cab side surface	15.36
11	Bearing frame of the cab roof	15.77
12	Cross rails of the body side walls	19.74

5. 2. Evaluation of the effect of structural deviations

The obtained frequency spectrum of the DS3 electric locomotive body is of interest in terms of its further analysis with regard to the effect of structural changes on it. For this, a number of the most characteristic and common defects known from the practice of operating machines of a similar type were modeled in the developed finite element model. These include cracks of various lengths of the base metal of the structural element, destruction of the weld of various lengths, destruction of the element of the bearing frame of the body and roof, as well as damage to the elements of internal bearing partitions.

In total, more than 100 various defects and failures of various sizes located in different parts of the bearing structure of the DS3 electric locomotive body were analyzed. It was found that all such defects reduce natural partial frequencies, leaving oscillation modes almost without qualitative changes.

The greatest effect on the frequency spectrum is provided by the location of the defect. The results obtained during modeling for different distances of damage from supporting nodes (connection nodes with other structural nodes) of the corresponding structural elements are given in Table 4.

Table 4

Changes in the partial frequency spectrum of the main structural elements of the DS3 electric locomotive body

No.	Structural element	Frequency (Hz) at the position of structural deviation at a distance from the supporting node		
		1/4 span	1/3 span	1/2 span
1	Binding frame of the roof top	1.85	1.73	1.52
2	Bearing frame of the cab floor	6.66	6.55	6.34
3	Side rails of the roof bottom	7.01	6.90	6.69
4	Bearing frame of the cab front surface	9.64	9.54	9.34
5	Side rails of the body floor	9.91	9.80	9.60
6	Bearing frame of the cab rear wall	10.23	10.13	9.93
7	Cross rails of the roof bottom	11.20	11.09	10.90
8	Cross rails of the body floor	12.05	11.94	11.75
9	Side rails of the body side walls	14.59	14.49	14.30
10	Bearing frame of the cab side surface	15.09	14.99	14.81
11	Bearing frame of the cab roof	15.50	15.41	15.23
12	Cross rails of the body side walls	19.49	19.40	19.23

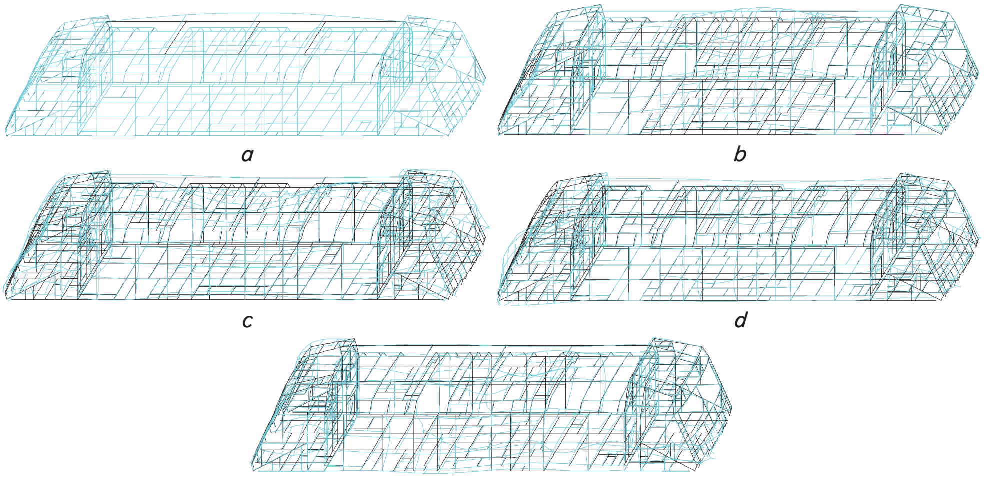

Fig. 6. Partial oscillation modes of the main structural elements of the DS3 electric locomotive: *a* – binding frame of the roof top; *b* – side rails of the body floor; *c* – cross rails of the body floor; *d* – side rails of the body side walls; *e* – cross rails of the body side walls

The minimum values given in Table 3 actually determine the range of possible changes in the spectrum of natural partial frequencies. As follows from the above data, the range of variation is wider for lower frequencies and less wide for higher frequencies. However, in all cases, this range is at least an order of magnitude greater than the experimental accuracy of frequency determination of 0.01 Hz. This confirms the possibility of detecting structural defects or deviations, as well as determining their approximate location by changes in the partial frequency spectrum of the electric locomotive body.

5. 3. Method of dynamic integral evaluation of technical condition

Thus, based on the data obtained, it is proposed to analyze the technical condition of one-section electric locomotives by dynamic integral evaluation. Based on the spectrum of partial dynamic characteristics of the one-section electric locomotive body and analysis of this spectrum, the method of dynamic integral evaluation of technical condition is developed. The essence of the method lies in the fact that the presence and location of the defect or damage are determined by changes in the frequency spectrum of a particular machine during operation. Practical implementation of this method for a specific electric locomotive is carried out in several stages performed sequentially.

Stage 1. The finite element model of the machine is developed with all the design features according to the design documentation. Moreover, the more accurately various nodes are modeled, the higher the reliability and accuracy of the data obtained. The natural dynamic characteristics of the machine, namely partial frequency spectrum and corresponding oscillation modes, are determined numerically.

Stage 2. During the initial test of the machine before putting it into operation, natural dynamic characteristics, primarily partial frequency spectrum are recorded. To do this, the strain gauge system is installed on all the main structural elements of the machine body and data is collected according to a shortened dynamic test program. The sensors are arranged in strict accordance with the partial oscillation modes of these structural elements of the electric locomotive obtained in stage 1 so that they are in the zone of maximum amplitudes.

Stage 3. Based on the data collected in this way, a special dynamic passport of a specific electric locomotive is compiled, which is stored throughout the subsequent life of the machine. It contains the partial frequency spectrum of the machine, oscillation mode corresponding to each partial frequency and information about the location of strain gauges.

Stage 4. Then, dynamic tests are repeated in the course of operation with a certain frequency, for example 0.5–1 years or any other, established by the manufacturer of the machine. The data obtained, primarily on the partial frequency spectrum, are entered in the dynamic passport of the machine and compared with the nominal values and, if necessary, the results of previous tests. Given the differences, it is quite easy to estimate the presence of any deviations in the design of the electric locomotive compared to the initial structural solution, as well as to identify the damaged structural element itself.

Note also that this method of dynamic integral evaluation allows determining not only the presence of any failure in the bearing elements of the electric locomotive, but also the location of damage in the structural element itself. Another important advantage of the proposed method is that faults arising during the operation of the electric locomotive can be detected even at the initial stages of their development. However, this is possible only under the condition of systematic constant monitoring with regular dynamic assessment of machine characteristics.

This method can also be applied to electric locomotives already in operation for a certain period of time. In this case, steps 1–3 are performed at a specific time of machine's operation and serve as a kind of reference point for further monitoring of its technical condition. Then, step 4 is periodically performed and, if necessary, structural damages, deviations or defects identified are eliminated.

5. 4. Practical testing of the method of dynamic integral evaluation of technical condition

To assess the efficiency of the method of dynamic integral evaluation of the technical condition of the electric locomotive, dynamic examination of the DS3-008 machine was carried out after one and a half years of operation. At the same time, all implemented structural changes were preliminary made in the finite element model in accordance with the machine modernization certificate. The resulting spectrum of nominal partial frequencies is given in Table 5. This table also shows the spectrum of real partial frequencies obtained from the results of dynamic examination using the strain gauge system (according to the scheme similar to Fig. 5).

Table 5

Partial frequency spectrum of the main structural elements of the DS3-008 one-section electric locomotive

No.	Structural element	Frequency, Hz	
		nominal	real
1	Binding frame of the roof top	2.83	2.75
2	Bearing frame of the cab floor	7.15	7.21
3	Side rails of the roof bottom	7.32	7.29
4	Bearing frame of the cab front surface	9.98	9.62
5	Side rails of the body floor	10.21	10.11
6	Bearing frame of the cab rear wall	10.53	10.50
7	Cross rails of the roof bottom	11.67	11.45
8	Cross rails of the body floor	13.21	13.18
9	Side rails of the body side walls	14.88	14.78
10	Bearing frame of the cab side surface	15.23	15.25
11	Bearing frame of the cab roof	15.77	15.70
12	Cross rails of the body side walls	19.89	19.86

As a result of the examination, a significant deviation in the frequency spectrum was found for the bearing frame of the cab front surface (shown in dark color in Table 4). This allowed for a more detailed technical inspection of the indicated location (the middle third of the structure), which revealed the presence of damage to one of the bearing rods. Note that during the preliminary standard maintenance procedure of the machine, this defect was not identified. Meanwhile, its presence led to a specific vibration of the electric locomotive control panel, which in practice complicated the control of this machine.

Thus, the applied method of dynamic integral evaluation of the technical condition for one-section electric locomotives confirmed its practical effectiveness. The method allowed not only identifying and eliminating one of the technical problems of the DS3-008 machine, but also preventing damage in other machine parts, which also revealed deviations in the partial frequency spectrum.

6. Discussion of the results of the study of dynamic characteristics of the one-section electric locomotive body

Based on the results of the study of dynamic characteristics of the one-section electric locomotive body, the spectrum of natural partial frequencies of its main structural elements is obtained (Table 3). It is found to be sufficiently dense and in the range of up to 20 Hz. At the same time, the first lower oscillation modes are node-free (Fig. 6). For higher oscillation modes, starting with the 8th, wave nodes (node modes) appear on individual structural elements.

Analysis of the effect of various structural deviations on the dynamic characteristics of the body potentially occurring in practice showed a tendency toward a quantitative change in the partial frequency spectrum to the lower direction (Table 4). The main determining factor is the location of the structural deviation. At its maximum distance from the points of coupling with other structural elements, a decrease in partial frequencies reaches 25–30 %. When the structural deviation is located closer to the nodes, the decrease in the partial frequencies is less noticeable, but in all cases it exceeds the experimental accuracy of frequency determination equal to 0.01 Hz (Table 2).

This result made it possible to develop a specialized method of dynamic integral evaluation. It is used to assess the technical condition of the main structural elements of the one-section electric locomotive body. It lies in the fact that by changes in the frequency spectrum of a particular machine during operation, the presence and location of the structural deviation are determined. This allows solving the problem of timely and accurate detection of defects and damages arising in the elements of such machines (Section 2), instead of their accidental detection during repair or operation.

Practical implementation of the developed method for a specific electric locomotive is carried out in 4 stages performed sequentially (Section 5. 3). In this case, it is necessary both to create a sufficiently accurate finite element model of the bearing structure of the electric locomotive under consideration, and to conduct subsequent experimental dynamic tests of the machine. Based on their results, a dynamic passport is compiled, which is the main document for further assessment of the technical condition of the machine body.

Practical testing of the method of dynamic integral evaluation of technical condition was performed for the DS3-008 electric locomotive after a year and a half of operation (Section 5. 4). As a result, the deviation in the partial frequency spectrum obtained experimentally from the nominal one obtained by finite element modeling revealed the location of a potential emergency defect. After suspending the operation of the electric locomotive and conducting a detailed technical inspection of the specified structural unit of the machine, the frame of the cab front surface, the presence of damage to one of the bearing rods was revealed. The damage was only at the development stage and therefore did not lead to a node failure, which allowed timely prevention of a serious emergency.

The main limitation in the applicability of the method of dynamic integral evaluation of technical condition is the required high accuracy of creating a finite element model of an electric locomotive. This may require special design surveys if relevant documentation is not available. Also, the method requires sufficient qualifications of both the personnel developing the computer model of the machine and the personnel performing dynamic tests.

In the future, this method can be applied not only to the bearing structures of electric locomotive bodies, but also to other structural units, such as frames, bogies, or electric devices. However, this requires special preliminary studies of the dynamic characteristics of these elements. In addition, the use of the method of dynamic integral evaluation of the technical condition of the one-section electric locomotive body can also be recommended for other units of railway rolling stock after appropriate theoretical justification.

7. Conclusions

1. The spectrum of natural partial frequencies of the main structural elements of the one-section electric locomotive lies in the range up to 20 Hz. Moreover, it is sufficiently dense, which requires a fairly accurate determination of specific frequency and corresponding oscillation mode.

2. The presence of damage in the bearing structural elements of the one-section electric locomotive leads to a decrease in its frequency spectrum. For the most common types of defects in the practice of operation, such a decrease is 25–30 %. Moreover, the location of the defect can be determined by a quantitative decrease in the value corresponding to partial frequency.

3. The method for dynamic integral evaluation of the technical condition of the bearing structural elements of the one-section electric locomotive body is developed. It lies in the fact that the presence and location of the defect or damage are determined by changes in the frequency spectrum of a particular machine during operation.

4. The efficiency of the developed method of dynamic integral evaluation of the technical condition of the one-section electric locomotive body was tested on the example of the DS3-008 machine. The method allowed not only identifying and eliminating one of the technical problems of the DS3-008 machine, but also preventing damage in other machine parts, which also revealed deviations in the partial frequency spectrum.

Using the method of dynamic integral evaluation of the technical condition of the one-section electric locomotive body can also be recommended for other units of railway rolling stock. The only prerequisite is a preliminary theoretical study of the main parameters of partial dynamic characteristics of certain machines for the presence of any features.

Acknowledgments

The authors of the paper express their gratitude and appreciation to the staff of the Dnipro Electric Locomotive Plant for the kind opportunity of unlimited access to the structural part of the DS3 electric locomotives. At the same time, the authors would especially like to note the chief designer of the DS3 electric locomotive PhD Andrei Yaroslavovich Grivnak and the head of the design department of the research institute of the plant Georgy Alexandrovich Rosenthal.

Also, the authors would like to express special gratitude to the team of developers of the SCAD for Windows design and computing complex PhD A. V. Perelmuter, PhD M. A. Perelmuter, PhD V. S. Karpilovsky, E. Z. Kriksunov, O. M. Trofimchuk. At the time, they kindly and gratuitously handed over the working version of this complex to one of the authors of the paper (D. O. Bannikov) for conducting scientific research and practical calculations.

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