Fault-tolerant nondestructive control of the stress-strain state of the load-bearing elements of pantograph lifts

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Abstract. This paper proposes a method of fault-tolerant nondestructive control of the stress-strain state of the load-bearing elements of lift and transportation machines, considered on the example of a prototype of pantograph-type lifts. The basic requirements for the load-bearing elements of lift and transportation machines are analyzed. An experimental research technique has been developed including tensometric and thermal nondestructive testing methods. A full-scale experiment of a prototype pantograph-type lifts is shown.

1. Introduction
There is a class of lift and transportation machines (LTM), the development, testing and production of which have certain features. Such special purpose vehicles include a mobile communications system based on a KAMAZ off-road vehicle with a mounted pantograph-type lift with a mast lifting height of 32 m with a payload of up to 1 ton and the ability to work in harsh climatic conditions of the Far North: in particular, ambient temperature ± 60°C, wind speed up to 30 m/s. Operation feature of this machine is that each lift/lowering cycle involves constant and continuous exhaustion of the resource of the metal structure of the lift and traction ropes of the lifting mechanism. Despite the use of high-strength steel in the design of the lift, the need to reduce weight and size indicators makes it necessary to ensure the functioning of the lift in the field of weak plastic deformations. Traditionally, tensometric control method is used during acceptance test of prototypes of LTM designs [1-2]. The method of thermal nondestructive testing (NDT) based on the mechanism of deformation heat generation today has significant prospects for implementation when testing LTM [3-9]. During operation, it is advisable to use only the latter method.

The main requirement for the LTM metal structures is to maintain the bearing capacity, while the deflections and deformations are not standardized in the general case, and, therefore, in order to save design, it is possible to use all the resources of the plastic work of the material. In fact, the design must have the property of survivability when exposed to short-term dynamic loads. The application of the methods of survivability theory of technical systems and static and dynamic estimates of the functioning of technical objects allows us to more accurately determine the residual life of LTM metal structures, after the impact of normative and excess dynamic loads [10-17].

The purpose of this work is to provide fault-tolerant control of the stress-strain state of the LTM and, in particular, pantograph-type lifts.
2. Method of experimental research
The developed method of fault-tolerant control of the stress-strain state of the LTM and, in particular, pantograph-type lifts is explained by the diagram (figure 1).

The LTM or pantograph-type lifts 1 subjected to static or dynamic testing in standard and excess operating modes were analyzed. To do this the measured values of the primary transducers 2 are preliminarily calculated based on mathematical modeling with the specification of the geometric dimensions of the final element, taking into account the geometric dimensions of the primary transducers and the operating ranges of the controlled quantities. According to the results of mathematical modeling the primary converters were installed at the points of checking the output operating parameters of the tested LTM or pantograph-type lifts.

Figure 1. Scheme of the method of ensuring fault tolerance and reliability of test results.

To ensure the reliability of the recorder information, we simultaneously register the readings of all the sensors of the operating parameters with the start frequency for registration \( f_{\text{reg}} = K_f f_m \), where \( K_f \) is the multiplicity factor of the start frequency \( K_f \geq 2 \), \( f_m \) is the maximum frequency of vibration diagnostics in the machine design. The recorded signal was converted with the on-board recorder 3 (with the ability to connect an external computer 9) using an analog-to-digital converter with a range
of at least 16 bits and a trigger frequency of 7 kHz, for example, using the MIC-400 measuring and computing complex, which is configured before the test by the number and type of sensors used. The measuring channels are configured according to the amplitude of the measured signals and the start frequency for the measurement, and then the necessary memory capacity of the recorder 3 is calculated and provided.

In order to ensure protection against loss of data from test results, the recorded information is transferred remotely during the test by radio channel or with the help of a cellular network 4 to a terminal with a built-in computer and a connected external computer 9 located outside the tested machine. The signals received by the terminal are additionally recorded for storage in an additional non-volatile memory 5 with the ability to read if necessary. Besides, the test data is additionally transferred to a special site using the Internet global network with the possibility of remote access to them.

The measured values of the metal structures of the tested machine are registered. To do this, we register the magnitude of the forces applied to the design of the machine using force sensors. Also, we register the distributed load applied to the reference points of the machine structure using the sensors of the support reactions. Stresses and deformations of machine structural elements are measured with the help of strain gauges. Contact or non-contact linear displacement sensors are installed at the points of deflection control for the metal structures of the tested machine relative to the support platform and (or) the ground. Micromechanical inertial converters are installed on the supporting platform (chassis) of the tested machine, on the movable elements of metal structures. We register mechanical vibrations and accelerations of metal structures with piezoelectric accelerometers and micromechanical inertial transducers, and record deflections and variations in the position of structural elements during the movement of the machine using linear displacement sensors and micromechanical inertial transducers.

During the experiment we register the measured values of the drive units of the tested machine. To do this, the pressure values of the hydro and pneumatic systems are registered with the use of pressure sensors. We also register the parameters of the drive units using sensors of active powers, current, voltage, power frequency, torque, speed, and temperature. The parameters of the external environment are registered using an anemometer, thermometer, hygrometer and barometer. Large strain gauges are installed on cables, and temperature sensors are installed on drive motors. We register the operating modes of the drive motors with sensors of active power, currents, voltages, frequency of the supply network; torque sensors and speed sensors are installed on the shafts of the drive motors.

We also register environmental parameters 6 when testing the machine. For registration, we use instruments such as an anemometer, thermometer, hygrometer, barometer that are installed on the tested machine.

The stress-strain state of the metal structures is additionally remotely recorded with a thermal NDT 7. Geometric dimensions of the tested machine and their changes in time are additionally remotely recorded with digital cameras and a video camera 8 with high resolution. In this case, the stress-strain state of the metal structure is simultaneously recorded using tensometry method at individual points of the structural unit, and by phototensometric method throughout the structural unit or its part, and by the thermographic method throughout the structural unit or the entire machine structure. Then, the test data obtained by direct and indirect methods are compared and, if necessary, supplemented, which ensures fault tolerance and reliability of measurements during excess tests of machine survivability.

3. Experiment
Due to the experimental studies and processing of the test results of a prototype pantograph-type hoist (figure 2,3) new statistical data were obtained for the applied methods of nondestructive testing. The method of tensometry allowed sufficiently accurate evaluation of the structure stress-strain state for compliance with the declared characteristics of the terms of reference. The method of thermal NDT based on the mechanism of deformation heat generation was synchronously used during testing (figure 4,5), and processing the data obtained allows us to develop a rapid diagnostic technique for fault-tolerant control of stress-strain state of LTM structures.
The scale division value or the least significant unit for each measuring system is determined by the formula (1):

$$1\delta_i = \varepsilon / \Delta C$$  \hspace{1cm} (1)

where \( \varepsilon \) – the relative value of the deformation in the structure, \( \Delta C \) – are the readings of the system when determining the unit of the least significant bit.

The unit of the least discharge of the thermal NDT method based on the mechanism of deformation heat generation was obtained on the basis of comparison with tensometry data. The change in strain is converted to heat in the temperature field range specified by the limits of the thermal imaging measuring equipment.

4. Conclusion

Thus, the study shows that the measurement of strains and stresses is ensured by the application of the tensometric method, which has sufficient measurement accuracy, but the obtained test information is limited by the areas of strain gauges installation. A method of fault-tolerant control of the stress-strain state of the LTM metal structures has been developed, which is provided by the use of a duplicate, indirect, remote method for measuring mechanical stresses and strains using infrared thermography. Panoramic studies of critical structures allow for express control during the operation of machines. A method for determining the scale division value of the thermal NDT method based on the mechanism of deformation heat generation is developed.
References
[1] Bekher S A, Kolomeets A O 2016 Calibration methods of force control diagnostic system of a rolling stock on the run. J. of Phys. Conf. Series 671(1) 012029
[2] Bekher S A 2016 Regularities of acoustic emission in the freight car solebar materials J. of Phys. Conf. Series 671(1) 012005
[3] Moysyeychik E A, Vavilov V P 2018 Analyzing patterns of heat generated by the tensile loading of steel rods containing discontinuity-like defects Int. J. of Damage Mechanics 27(6) 950-60
[4] Vavilov V P 2017 Infared nondestructive testing of materials and products: a review Russian J. of Nondestructive Testing 53(10) 707-30
[5] Moysyeychik E A, Vavilov V P, Kuimova M V 2018 Infared thermographic testing of steel structures by using the phenomenon of heat release caused by deformation J. of Nondestructive Evaluation 37(2) 28
[6] Sharkeev Y P et al. 2019 Infared thermography and generation of heat under deformation of bioinert titanium- and zirconium-based alloys Russian J. of Nondestructive Testing 55(7) 533-41
[7] Zorin V A, Bausova N I, Kosenko E A 2017 Detection of defects in components made of dispersion-filled polymeric materials by the method of infrared thermography Polymer Sci. Ser. D 10(3) 241-3
[8] Kaur K, Mulaveesala R 2019 An efficient data processing approach for frequency modulated thermal wave imaging for inspection of steel material Infrared Physics & Technology 103 103083
[9] Ahmad J, Akula A, Sardana H K, Mulaveesala R 2020 Defect detection capabilities of independent component analysis for barker coded thermal wave imaging Infrared Phys. & Technol. 104 103118
[10] Odnokopylov G I, Sarkisov D Y 2017 Evaluation of breaking load parameters under shock wave loading for critical constructions of oil and gas sector facilities Bulletin of the Tomsk Polytechnic University, Geo Assets Engineering 328(3) 85-95
[11] Odnokopylov G I, Sarkisov D Y, Butuzov E A 2018 Evaluation of survivability degree of responsible building structures under shock wave loading Bulletin of the Tomsk Polytechnic University, Geo Assets Engineering 329(12) 122-35
[12] Odnokopylov G I, Kumpiyak O G, Galyaughtinov Z R, Galyaughtinov D R 2019 Determination of vitality parameters of protected critical engineering structures under shock-wave loading Bulletin of the Tomsk Polytechnic University, Geo Assets Engineering 330(4) 110-25
[13] Odnokopylov G I, Shevchuk V A, Dementyev Y N 2019 Application of system analysis for providing reliability of electrical machines in diamond industry Bulletin of the Tomsk Polytechnic University, Geo Assets Engineering 330(5) 131-40
[14] Makhtutov N A, Reznikov D O 2019 Assessment of large-scale catastrophes in complex engineering systems IOP Conf. Ser.: Mater. Sci. and Engin. 012002
[15] Makhtutov N A, Razumovskii I A 2018 Method for the analysis of residual stress fields in spatial details Inorganic Materials 54(15) 1503-10
[16] Makhtutov N A, Gadenin M M, Lepikhin A M, Shokin Y I 2018 Justifying calculations of the security of promising machines and man-machine systems on the risk criteria of accidents and disasters J. of Machinery Manufacture and Reliability 47(5) 442-50
[17] Makhtutov N A, Reznikov D O 2018 A generalization of neuber's rule for the assessment of local stresses and strains in stress concentration zones for a wide range of applied strains Proc. of 2nd Int. Structural Integrity Conf. & Exhibition (SICE - 2018) (Hyderabad: Publ. & Polygr. Unit, DMRL) pp 24-5