Increase of Technical Condition Control Efficiency of Marine Railways

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Abstract. The paper presents the result of solving a relevant scientific and practical problem, which consists in the development of methods and diagnostic tools and improving the efficiency of monitoring the technical condition of transport equipment, in particular elements and units of marine railways, through the introduction of an automated system for diagnostics and monitoring of technical condition, which provides an increase in the reliability of diagnosis, reducing the time and cost of diagnostics. The analysis showed that the existing methods for determining the main parameters of the technical condition of elements and units of slips, which are the basis for reliable diagnostics of the technical condition, need to be improved. A method has been developed for monitoring the integrity of the main elements of marine railways based on the analysis of the temperature and natural vibration frequency of the main elements, which, in contrast to the existing methods, gives an error in measuring the signal frequency of less than 0.05%, which makes it possible to determine defects at early stages of their development.

1. Introduction
Structures for lifting and lowering vessels on inclined planes are the most common when docking vessels. These include boathouses and slipways - lifting equipment and structures for the construction, repair, lifting and lowering of a vessel, craft, or floating object.

For installation, survey, inspection, repair, and maintenance of recessed, rowing, steering and thrust mechanisms, deadwood seals, intake valves, underwater part of the hull, the vessel must be lifted from the water or have dry parts during its laying and construction.

For docking ship repair and shipbuilding enterprises use various lifting and lowering mechanisms, ship lifting equipment and structures for lowering and lifting ships and crafts: boathouses, slipways, dry, bulk and floating docks and vertical ship lifts [1].

Marine railways are known to be characterized by large amounts of capital investment, complexity, heterogeneity of soil conditions and loads. Therefore, new design solutions to monitor the technical condition, clarifying the features of the structure, can give a significant economic effect.

Many years of research experience show that buildings in operation are exposed to various factors that affect the value of bearing capacity. Factors influencing the bearing capacity include the following: construction technology, mode of operational loads, damage to the structure, rheological phenomena in the materials of structures and base soils, environmental influences, etc.

Many works cover theoretical and practical issues of rational operation of port waterworks [2, 3, 4, 5]. The question of influence on constructions of static and dynamic loadings is stated [6, 7, 8, 9]. Considerable attention is paid to the analysis of the impact of time factor on buildings. Methods of
calculation of structures operated for long-term strength are given, which allow to estimate the bearing capacity of structures depending on their age and on this basis to assign the required mode of operation [10]. Technical means, methods of observations and research on the condition of structures are described in [11, 12, 13, 14, 15, 16].

To ensure guaranteed and normal operation of port and ship-lifting hydraulic structures, it is necessary to conduct systematic monitoring to identify the actual technical condition of structures and assign an appropriate mode of operation [17].

2. Problem statement
Shipyards play an important role in solving the problem of providing the necessary conditions for the functioning of the sea and river fleet. The vast majority of shipyards in Ukraine and around the world use slipways in their production activities. Slipways, i.e., marine railways with a base in the form of reinforced concrete beams on piles or pile base, are the most common in the world shipbuilding and ship repair industry. Slipways belong to transport equipment [18], which performs the role of in-house transport, used in the technological process of ship repair, and provides drainage of the underwater part of the ship for its inspection and repair. Transport equipment is a type of transport that is used for periodic movement of goods on the territory of the plant or enterprise to production sites or shops [18].

Execution of the tasks assigned to slipways must be ensured by the efficient operation of the complex of its technical means. Improving the process of technical operation can be achieved in two ways:
- the first is associated with improving the technical level of operation, improving the elements of this system, including the creation of high-tech and reliable elements and units of the slipway;
- the second way offers improvement of control system of efficiency of process of technical operation, including substantiation of programs on maintenance and current repair of elements and units of a slipway, creation of programs of prediction of their residual resource and creation of modern means of control of parameters and technical diagnostics of elements and units of a slipway based on automated systems of diagnostics and control of the technical condition, i.e. Distributed Measurement System (DMS) in order to ensure quality repair and maintenance of ships.

Periodically it is necessary to solve the problem of technical operation of slipways in conditions of reduced level of readiness of technical means [19], which occurred due to various damages of elements or units [20]. It is especially difficult to make decisions in emergency modes when improper control can lead to catastrophic consequences.

In this regard, it is important to develop methods and tools for diagnosing and monitoring the technical condition of the elements and units of marine railways [21]. The main features that characterize the technical condition of marine railways is the integrity of the elements and physical wear of units. The main parameters of the technical condition, uniquely related to the integrity of the elements of the marine railway, are the temperature of the element and the natural frequency [22].

This work is devoted to solving the scientific problem, which is to develop methods and tools for diagnosing and improving the efficiency of monitoring the technical condition of transport equipment [23], in particular elements and units of marine railways, through the introduction of automated diagnostic system and technical condition monitoring of DMS, which increases the reliability of diagnosis, reduces time and cost of diagnosis.

3. The general concept of increase of technical condition control efficiency of marine railways
Inspection and operational control of the technical condition of port waterworks form a comprehensive system of technical control of these objects, which ensures the efficient use, preservation, and safety of operation of structures during the established period of their service [24].

Inspections of structures are divided into:
- primary comprehensive inspections which are carried out not later than six months after the commissioning of facilities;
- regular comprehensive inspections which are conducted at least once every five years (after the expiration of the certificate of the structure suitability for operation) [25];
- extraordinary inspections which are carried out in violation of regulatory conditions of operation, when there are reasonable doubts about the performance of structures, in the event of accidental damage to structures, as well as after reconstruction or overhaul;
- special inspections (observation of general and local deformations and displacements of structures [26], their experimental loading, inspection of soils of bases and backfilling, dissection of recessed elements of structures) which are performed in cases of signs of unacceptable deformations and deviations of design height from design values [27].

Operational control of the technical condition of structures is carried out to ensure their safe operation by timely detection of defects and violations of the mode of operation and taking measures to eliminate these defects and violations [28]. The methodology and scope of technical inspections and observations for control, including measurements, should ensure the reliability and completeness of the information obtained to prepare a reasoned conclusion on the current technical condition of facilities and develop measures for their maintenance to ensure safe operation [29].

The development of intelligent systems for assessing the technical condition is to develop special algorithms that help staff to make the right decision about the technical condition at the moment.

The application of the principle of continuous analysis, in which the software complex with the help of special devices automatically analyzes the current operating conditions and gives special adapted recommendations to service personnel and the operator, is a promising area of technical operation.

The principle of remote diagnostics provides continuous operational control of the technical condition of systems and a design of marine railways and detection of the condition before failure. Remote diagnostics is a process of determining the technical condition of the diagnosis object at a distance, by receiving signals from sensors installed on marine railways.

The use of technical control systems of marine railways, which have the functions of collecting and transmitting information about the current state, help to take additional measures to reduce the risk of unforeseen failure of systems and units, will not only continuously perform the work for a longer time, but also increase useful life in general.

The purpose of technical condition control is to determine the actual technical condition of marine railways, ensure their serviceability, and check the suitability for their safe use, the reliability of the descent and ascent of water transport and protection of human life.

The main functions of the technical diagnostic system are:
- assessment of the marine railway technical condition;
- search for faults and reasons for failure;
- predicting of technical condition.

The general scheme of directions of increase of technical condition control efficiency of marine railways is given in Figure 1.

The main role of the introduction of technical condition control systems is to improve the quality of control, reduce the errors of operators and facilitate their work [30]. Due to these changes, the level of competitiveness on the market is growing, there is a strong increase in the use of the resource base.

Improving the reliability and efficiency of operation of ship lifting and ship repair equipment required the widespread use of technical diagnostic components to assess and predict the actual technical condition of the equipment [31].

Improving the strategy of operation and maintenance of ship lifting and ship repair equipment can be achieved only with a comprehensive approach to the development and implementation of appropriate diagnostic software.

Diagnostic support systems are faced with the task of choosing a rational strategy for equipment maintenance; the level of diagnosis and structural parameters that characterize its technical condition;
diagnostic methods and diagnostic parameters; methods of measuring diagnostic parameters; algorithms for selecting diagnostic information; diagnostics hardware; methods of prediction and estimating the residual resource.

Figure 1. Directions for increasing technical condition control efficiency of marine railways

4. The problem solution of the technical condition control of marine railways

The optimal problem solution of determining the technical condition of complex objects can be obtained only by analyzing the set of technical conditions $W$, in which these objects can be in operation. This analysis can be performed both theoretically and experimentally.

The construction of recognition algorithms in diagnostics is significantly facilitated in the case when it is possible to build a diagnostic model that establishes a relationship between the condition space and the space of diagnostic features. It does not matter in what form this relationship is presented.

The diagnostic model meets the purpose in the case when it allows:
1) formulating the conditions for dividing set $W$ into two subsets of valid $W'$ and faulty $W''$ conditions;
2) obtaining criteria for assessing the performance of the diagnostic object (distinguishing conditions in subset $W'$);
3) establishing the signs of malfunctions that have occurred (distinction of conditions in subset $W''$);
4) establishing correspondence between the space of conditions $W$ and the space of diagnostic signs $D$.

The choice of the model type depends on such factors as operating conditions, design, type of components, the nature of the interaction of parts, the conditions of oscillation excitation, the nature of the objective function, etc.

Differential and algebraic equations, logical relations, matrices of nodal conductivities, functional, structural, regression and other models that allow connecting the technical condition parameters with the characteristics of the object can be considered as diagnostic models [32].

Representation of a real object by a diagnostic model allows distracting from its physical nature and formalizing the solution of diagnostic problems.

In order to develop any method and technology for diagnosing a complex unit, it is not enough to know the patterns of change in the parameters of its individual components. It is necessary to have a generalized logical or analytical description of the most important properties of the whole object,
which should include a list of elements that fail most often, which structural and diagnostic parameters
and the relationships between them correspond to these elements.

The simplest logical description of the control object is expressed by the structural and
consequential scheme shown in Figure 2.

![Figure 2. Structural and consequential scheme of the diagnosis object](image)

The structural and consequential scheme is created on the basis of engineering study of the object
structure and functioning, the statistical analysis of indicators of reliability and diagnostic parameters.
It gives a clear idea of the most vulnerable and most responsible elements and relationships of
structural and diagnostic parameters. Using this scheme, you can choose the most important diagnostic
features, therefore, methods and means of diagnosis [33].

Based on common sense and design of the marine railway, as a model applicable to search for the
most important diagnostic features of the technical condition, we choose a regression model.

The process of changing the parameters of the technical condition of the mechanism during its
operation is multifactorial. Given the limited capabilities of the statistical data set due to the high cost
of diagnostic tests, the most effective method is to build an analytical model that links the diagnostic
feature with the technical condition relevant parameters [34]. This method is based on the use of a
mathematical apparatus for planning the experiment and allows finding a "characteristic" diagnostic
feature, clearly associated with the technical condition relevant parameters. Thus, among the many
technical condition diagnostic parameters of the elements of marine railways two parameters were
found, i.e., temperature and natural frequency, which are clearly associated with such a diagnostic
feature as the integrity of the marine railway elements.

Experiment planning is a procedure for selecting the number and conditions of experiments
necessary and sufficient to solve the problem with the required accuracy. The obtained approximate
equation of relationship of technical condition parameters \( m_i \) (factors) and diagnostic sign \( q \) (response
function) is called regression equation. In the case under study, to create a model for monitoring the
technical condition of marine railways, a good approximation was given by a linear regression model:

\[
q = a_0 + \sum_{i=1}^{k} a_i m_i + \sum_{i=1}^{k} \sum_{j=1}^{k} a_{ij} m_i m_j
\]

(1)

where the second sum characterizes the effects of the interaction of \( k \) normalized factors.

The problem of modeling is to find the regression coefficients \( a_i \) and assess the adequacy of the
model in accordance with certain rules [35]. The number of equations in system (1) is equal to number
\( p^k \) where \( p \) is the number of discrete levels of varied technical condition parameters, which must meet
the requirements of independence, compatibility, and controllability; \( k \) is the number of factors.

For example, for a marine railway, the number of discrete levels \( p = 3 \) is taken, as well as the
number of factors is \( k = 2 \). The number of equations of system \( p^k = 3^2 = 9 \) is calculated.

In the process of processing the results of the experiment the following values are evaluated:
1) The variance of the response function according to the results of \( n \) parallel experiments is

\[
S^2 = \frac{\sum_{i=1}^{n} (q_i - \bar{q})^2}{n-1}
\]

(2)

where \( \bar{q} = \frac{\sum_{i=1}^{n} y_i}{n} \) is mathematical expectation; \( n - 1 \) is the number of degrees of freedom.
2) The variance of the response function reproducibility according to the results of all experiments is

\[ S^2_{\{y\}} = \sum_{q=1}^{N} \frac{\sum_{i=1}^{n}(q_{ri} - q_{\bar{r}})^2}{N(n-1)}, \quad i=1,2,...,n; \quad r=1,2,...,N; \]  

(3)

3) Estimation of variance homogeneity according to Fisher’s test is

\[ \frac{S^2_{\text{max}}}{S^2_{\text{min}}} < F_T, \]  

(4)

where \( F_T \) is a tabular value of \( F \)-test at the selected level of significance.

4) Regression coefficients are

\[ a_j = \frac{\sum_{i=1}^{N} q_i m_{ji}}{N}, \quad j = 0, 1, 2, ..., k; \]  

(5)

5) The confidence interval of the regression coefficient is

\[ \Delta a_j = \pm t \frac{S_{\{y\}}}{N}, \]  

(6)

where \( t \) is a tabular value of Student's test at the number of degrees of freedom with which \( S^2_{\{y\}} \) was determined at the selected level of significance [36].

6) The model adequacy is

\[ \frac{S^2_{\text{ad}}}{S^2_{\{y\}}} < F_T, \]  

(7)

where \( S^2_{\text{ad}} = \sum_{i=1}^{N}(q_i - \bar{q})^2 \) is the adequacy dispersion; \( \bar{q} \) is the response function estimated value.

Based on the analysis of the results of calculations of the dependence of natural frequency on changes in temperature and density of marine railway elements using software for finite element analysis and multiphysical modeling COMSOL Multiphysics, an analytical model (8) of the dependence of the main load factor \( q_i \) on two parameters, i.e., temperature and natural frequency, was obtained as follows:

\[ q_i = a_0 + a_T T + a_F F \]  

(8)

where \( T \) is the temperature of the main bearing marine railway elements, °C; \( F \) – natural frequency of the main bearing marine railway elements, Hz; \( a_0, a_T, a_F \) – coefficients of the two-parameter model, which are determined using the Levenberg-Marquardt optimization method.

The graph of the dependence of the integrity factor of the main bearing marine railway elements is presented in Figure 3, where the green color on the plane reflects the serviceable technical condition of the element, the red color reflects the faulty technical condition. The yellow and orange one characterizes the transition between technical conditions.

The integrity factor of the main bearing marine railway elements \( q_i \) is a quantitative characteristic of the technical condition, which characterizes the physical wear of the structure and is the ratio of the actual natural frequency \( F \) and the expected natural frequency \( F_1 \) for the integral element (\( q_i = 1 \)) at temperature \( T \).

For the model shown in Figure 3, the following coefficients were obtained by means of the Levenberg – Marquardt optimization method using the MATLAB application package: \( a_0 = -0,000875 \); \( a_T = 4,377e^{5} \); \( a_F = 0,0556 \).

In order to use the model (8) in the software, the physical content of the shock pulses should be determined. The oscillations of a body subjected to external mechanical influence can be conditionally
decomposed into three components: Transverse oscillations, Longitudinal oscillations, and Torsional oscillations.

Figure 3. Graph of the dependence of the integrity of the main bearing marine railway elements on the temperature of the element and the natural frequency

It should be noted at once that torsional oscillations fall out of the scope of the presented work. Transverse oscillations are nothing but vibrations of elastic deformation or oscillations of the body relative to the state of rest [37].

The dependence of oscillations on time is in the simplest case a damped sinusoid (Figure 4).

Figure 4. Rapidly damping oscillations of the pile after impact
Longitudinal oscillations are oscillations of geometric dimensions of a body (stretching-compression) at cross deformation under the influence of external mechanical influence.

When registering the dependence of the signal on time, it is a rapidly damped transient (Figure 4). Their amplitude depends on the geometric dimensions and material of the deforming body, as well as on the strength of external influences, frequency - on the geometric dimensions, material, and body temperature. These signals are informative at diagnosis.

In practice, such a signal is difficult to record using a conventional piezo accelerometer, because it is associated with a number of difficulties associated with signal filtering and the dependence of the frequency response of the accelerometer on the installation method.

DMS developed by the authors uses Pt1000 resistance thermometers to measure temperature and sensors that detect vibrations that occur during shocks, i.e., a strain gauge sensor and a microelectromechanical three-axis accelerometer.

The criterion of absence of pile malfunctions and its serviceable condition (Figure 5) is the ratio of ADC frequencies and natural oscillations of the pile after impact. The frequency of natural oscillations of the pile, at a constant temperature, depends on the shape and material from which the pile is made, this frequency remains unchanged, as long as its technical condition is in good condition. Impacts occur at the time of passage of the vessel when descending into the water on the runways of the slipway. The pile goes into a faulty technical condition (Figure 6) after the loss of integrity.

**Table 1.** Results of an experiment to estimate the relative error of frequency measurement without (Discrete Frequency) and with (Refined Frequency) using the method of refining the results of the fast Fourier transform.

| Frequency, Hz | Discrete Frequency, Hz | DF error, % | Refined Frequency, Hz | RF error, % |
|---------------|------------------------|-------------|-----------------------|-------------|
| 1             | 1.012                  | 1.20000     | 0.99998               | 0.00200     |
| 50            | 49,805                 | 0.39000     | 49.998                | 0.00400     |
| 120           | 120,117                | 0.09750     | 119.996               | 0.00333     |
| 150           | 150.390                | 0.26000     | 149.993               | 0.00467     |
| 200           | 200.195                | 0.09750     | 199.991               | 0.00450     |
| 400           | 400.391                | 0.09775     | 399.984               | 0.00400     |

When processing a time-dependent signal containing information about the natural frequency, in order to eliminate the incoherence of the signals, resampling and decimation with a fractional coefficient were used. Improving the accuracy of signal frequency measurement was implemented by the author's method described in [33], the authors demonstrated the effect of using the described method to refine the results of the fast Fourier transform and obtained the accuracy of signal frequencies with an error of 0.005%. The use of DMS in the method of refining the results of the fast Fourier transform described in the article [33, 38] allowed to determine the natural frequencies of the main bearing marine railway elements with an error of 0.05%. Verification of the diagnostic information processing algorithm and evaluation of the accuracy of the method of refining the results of the fast Fourier transform was performed using an electrodynamic vibrating stand IMV m030/MA1...
(Figure 7) manufactured by IMV Corporation [http://www.imv.co.jp] and DMS hardware and software. Figure 8 in red columns shows the value by which the error in determining the frequency of oscillations without (top of the column) and with (bottom of the column) is reduced using the method of refining the results of the fast Fourier transform described in [33, 39]. Summary results of the experiment are presented in Table 1. In contrast to laboratory conditions in which the relative error of frequency measurement was not more than 0.00467%, in real operating conditions of DMS at the facility relative errors of frequency measurement not exceeding 0.05 % were obtained.

Figure 7. Electrodynamic vibrating stand manufactured by IMV Corporation [http://www.imv.co.jp] Figure 8. Comparison of the relative error of determining the oscillation

5. Conclusions
The study of modern and promising systems for monitoring the technical condition of marine railways determines that at present the possibility of intensive development of traditional systems for measuring technical parameters is almost exhausted. Further increase of reliability and efficiency of operation of marine railways demands the expanded application of components of technical diagnostics for estimation and prediction of an actual technical condition of marine railways. Therefore, the most promising area of improvement of these systems is their combination, integration and implementation of new relevant models and methods in a distributed measurement system.

Modeling the dependence of the integrity factor of the elements of marine railways using elastic and resilient-plastic models made in COMSOL Multiphysics, shows that the development is functional because it establishes a relationship between stresses and strains. The model is adequate, and the software used is quite reliable. Due to the use of fast mathematical tools, the model is quite effective.

Also, the task of developing a method for determining the technical condition of ship-lifting hydraulic structures on the basis of a two-parameter model of the technical condition control of marine railways is relevant. The mathematical model is offered in the article, which in turn determines the scientific result, i.e. the method of control of the integrity of the main elements of marine railways.

The authors present the general concept of improving the technical condition control efficiency of marine railways, two-parameter model, and method of determining the technical condition of load-bearing elements of marine railways, which are implemented in DMS hardware and software.

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