Methods of the building of the dynamic models of the drive machines loads with the use of system monitoring data (on example of the acceleration of the drive of the drill tool)

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Abstract. The article considers the sequence of modern machines’ monitoring systems data processing. The aim is to build the mathematical models of the complex dynamic processes of the interaction between working bodies of the machines with external ambience. On the example of drilling machines on the starting and accelerating modes of the drilling tool, the authors obtained the dependencies of the torque on the output shaft of the rotation drive of the drill string depending on the frequency and rotation acceleration, and the depth of drilling related to the rock strength.

1. Introduction
Mathematical modeling of machines is a common method of studying their dynamic processes of motion: acceleration/deceleration, automatic control, and special high-speed operations. Usually these studies are carried out to synthesize the optimal parameters of control devices, to determine the properties of a system under extreme conditions, and so on. Scientists usually use a systematic approach [1] for compiling mathematical models of machines. This approach presents a machine as a system consisting of separate subsystems: the main engine, transmission, and a working body interacting with the environment. To control the machine they use a control subsystem that imitates the actions of an operator or an ACS subsystem — an automatic control system. In general, the scheme of such a system can be depicted as in Figure 1. For a particular machine and depending on the research problem to be solved, the blocks of subsystems can be represented by subsystems of a smaller order, up to individual elements - devices.
The method of element-node structures proposed in [2, 3] and developed in the work of the author [4] is becoming more widespread in mathematical modeling of machines. In this method, the calculated model of the machine is represented by a dynamic system with inputs and outputs, internal and feedback parameters. The equations are written explicitly, as a function of real time. The final system of equations is a mixed system of nonlinear differential and algebraic equations of a large order, which is solved by numerical methods [4]. If the mathematical models of the main engine (internal combustion engine or electric motor) and transmission elements are represented in the technical literature quite well and their properties are well-known, then modeling the subsystem “working body - environment” has problems. This is due to the fact that most of the equations of load on the working bodies of machines known in the literature [5, 6, 7, etc.] refer to the statics of machines. In these equations, the loads on the working bodies do not depend on the time of the process, on the speed of movement of the mechanism, on the time-varying parameters of the environment. It is not possible to use such equations in mathematical modeling of the dynamics of machines.

There is a need for mathematical models, where a change in the kinematic parameters of the machine system would lead to a change in the load parameters in real time. A graphic interpretation of the required “working body - environment” models for some machines is shown in Figure 2. There are no such models for specific types of machines in the technical literature. In this case, most researchers of the dynamics of machines are limited to the consideration of simplified models where the loads on the working bodies are modeled as typical signals used in the theory of automatic control: a single jump; linear loading, harmonic function, i.e. without feedback from changes in the kinematics of the working body. The use of typical loading signals of mechanisms does not always give the optimal solution for the required parameters of the drives and the ACS of the machine system.

Figure 1. A Block scheme of machine systems.

\[ y_j \quad y_i \quad \text{CONTROLLING INFLUENCES;} \]
\[ c_j \quad c_i \quad \text{A POWER PARAMETERS;} \]
\[ k_j \quad k_i \quad \text{AN KINEMATIC PARAMETERS.} \]
Due to the complexity of the physical processes occurring in the subsystem “working body-environment”, direct theoretical mathematical modeling of this link is an extremely time-consuming task. Empirical methods based on experiments in bench conditions are also difficult because of the complex similarity of the inertial masses of the working body, complex imitation of environmental parameters, high cost and labor intensity of bench studies [8].

2. Concept headings
The author's methodology [4] proposes to use data from monitoring systems of machine operation at the design stage of machines. These monitoring systems are installed on modern machines for diagnostics of parameters, for example, the so-called “black boxes” on airplanes. Previously, such systems, due to their high cost, were installed only on especially important machines, but now, with the reduction in the cost of electronic components, many machines are equipped with monitoring systems: mechanisms of movable bridges, sluices, gates of hydraulic dams, quarry excavators, gantry cranes, combined road machines, various kinds of technological plants, drilling rigs, etc. Data from these systems is usually used only after machine crashes and serves as a source of information on determining the causes of these events. In some cases, these systems are used for administrative control over the operation of machines and mechanisms and are aimed at ensuring the norms of proper and safe operation. But this data can also be used in the development of mathematical dynamic models of the working body interacting with the environment.

The data of the monitoring systems of machines consists of digital records of the values of various physical parameters in real time: displacements, forces, pressures, temperatures, stresses, etc. The developers of the monitoring systems usually display this data on the operator’s screen in the form of graphs that look like a cardiogram. But working with graphics is inconvenient and there is a need for numerical data. Numerical data is not always possible to obtain because the developers of monitoring systems do not always make them available. If such difficulties arise, it is recommended to contact the developers of monitoring systems. The obtained data requires system archiving and conversion to typical data formats. In addition, it is necessary to carry out data rationing on various grounds, for example, technological operations, climatic conditions, and environmental properties. Then we can get the required mathematical dependencies by the methods of mathematical processing, including statistical methods.
3. Results

As an example, let us consider the solution of a problem for drilling rigs, which bores oil and gas wells to a depth of 3000–3500 m. This corresponds to a class of installations with a lifting capacity of 250–320 tons. According to the classification of drilling rigs, such technical characteristics have fixed and cluster installations (mobile, on a rail track, for relatively short distances up to 1.5 km). Drilling rigs are machines with continuous action that combine the processes of rotation and supply of the working body (the drill string with a drilling tool). When a drilling tool interacts with the rock, a torque is generated at the output shaft of the drive mechanism - the moment of resistance, which value depends on the strength of the soil, the speed of rotation and the feed rate of the drilling tool. Similar processes take place on milling machines, multi-bucket excavators and many other machines.

A feature of modern designs of drilling rigs is a movable drive rotation of the drill string. Previously, the drive was placed on the drilling table permanently, but in modern designs it goes up and down (like a shuttle) with a winch along the guide beam. Such systems are called top drive systems (TDS). The developers of this equipment are mainly foreign firms. Russian drilling companies also began to use this tool, since it can significantly increase drilling productivity. According to import substitution programs in the Russian Federation, similar domestic TDSs are being created [9, 10, 11]. This work is a continuation of previously performed research [12] within the framework of the federal target program “Research and development in priority areas of the development of the scientific and technological complex of Russia for 2014–2020”. St. Petersburg Polytechnic University of Peter the Great, together with the industrial partner JSC SKB PN, commissioned and sponsored by the Ministry of Science and Higher Education of the Russian Federation, carries out the project “Developing and researching the principles of controlling the curvature vector of a small diameter well with the help of rotary controlled systems” (Agreement No. 075-15-2019-1403 of 06/20/2019. T & V RFMEFI57517X0138).

TDSs are equipped with monitoring systems, which records has the parameters of the drive operation processes are recorded for the entire period of drilling of each particular well. Figure 3 shows a fragment of one of these records, which shows some time-varying parameters of the TDS: the rotational speed V of the drill string, the torque M on the output shaft, the vertical displacement GS of the drill string. In this case, the recording of V and GS parameters is a result of direct measurement, and the recording of M values is the result of measurements of indirect parameters, such as current strength (electromechanical drive) or pressure (hydraulic drive), and calculations that are performed by the monitoring system controller. Such records are the initial data for subsequent analysis. However, not all monitoring systems of modern machines issue records in this form. There is no unification yet. Each monitoring system is an individual system of its developer and to obtain records in the form shown in Figure 3 the system may require some additional computational transformations.
Figure 3. Fragments of the TDS monitoring systems recording.

To solve a specific task, we selected only parts of transient processes of acceleration of the drill string from the records of general processes (for other tasks we can use the other areas). In the selected areas, we eliminated random parameter outliers and smoothed the parameters associated with the “noise” of the measuring instruments. As a result of this preparatory work, we formed a database of transients of rotation frequency and torque for different depths of drilling. We can look at the example of selected transient functions in Figure 4. One well can have from 150 to 300 processes of acceleration of the drill string depending on the length of the used drilling pipes. Due to the use of different type of drilling tool, the data bank for one well was divided into two parts: data for depths up to 700 m and data from 800 to 3500 m.

Figure 4. An example of transient process record of the acceleration of the drill string.
Studies have shown that it is not enough to display the torque function during acceleration of a drill string as a simple polynomial function of the speed of rotation of the drill string, as suggested by the authors of [13]. The method of controlling the speed of most machines, including on drilling rigs, is remote manual. The rate of increase of rotational speed, i.e. acceleration, may be different. Therefore, based on [14], the polynomial function should be represented as a sum of terms, which will include the acceleration of the rotation of the drill string.

In the general case, we used the following dependence for approximation

$$\tilde{M}(\omega, \dot{\omega}) = a\omega^h + b\omega + c\omega^2 + d\dot{\omega}^k + e\dot{\omega} + f\dot{\omega}^2 + g,$$  

(1)

where, $\tilde{M}$ – approximation moment, $\omega, \dot{\omega}$ – the speed and acceleration of rotation of the drill string, respectively, $a, b, c, d, e, f, g, h, k$ – dependency parameters.

We determined the coefficients of the approximating dependence (1) sequentially for each individual section of the acceleration of the drill string. These coefficients were calculated by solving the problem of multidimensional minimization of the standard deviation of the values of the approximating dependence $\tilde{M}$ on the processed source data $M$:

$$\min \frac{1}{N} \sum_{i=1}^{N} (\tilde{M}_i - M_i)^2 = \min_{a,b,c,d,e,f,g,h} \frac{1}{N} \sum_{i=1}^{N} (a\omega^h + b\omega + c\omega^2 + d\dot{\omega}^k + e\dot{\omega} + f\dot{\omega}^2 + g - \tilde{M}_i)^2,$$  

(2)

where $N$ – the number of values of the moment in each individual section of acceleration.

The calculations were performed in Matlab R2012a.

To solve this problem, we used the method of Nelder-Mead unconditional minimization, since it has a high rate of convergence and does not require the calculation of the gradient. The method consists of sequential movement and deformation of an irregular multidimensional simplex in the direction of the optimum point. The coefficients were found with a relative error of the values of the function and arguments of $10^{-5}$. The sought approximating dependence (or coefficients optimization) for the moment was obtained in several successive stages. After each minimization for a set of optimized parameters, one or several coefficients weakly dependent on depth were taken as constant values and excluded from the optimized parameters at further optimization stages.

As a result of processing the initial data at depths of drilling from 800 to 3200 m, it was found that the coefficients of degrees $h, k$ take the same little varying values $h = k = 0.55$. As a result, they were assumed constant and equal $h = k = 0.5$. Parameters $c, d, e, f$ do not depend on the depth of drilling and can be assumed as constant: $c = -2.1 \cdot 10^{-3}$, $d = -0.454$, $e = 1.14 \cdot 10^{-4}$. Parameters $a, b, g$ depend on the depth of drilling and should be considered as functions. Therefore, the dependence (1) can be written in the form:

$$\tilde{M}(\omega, \dot{\omega}, h) = \tilde{a}(h)\sqrt{\omega} + \tilde{b}(h)\omega - 2.1 \cdot 10^{-3} \omega^2 - 0.454\sqrt{\omega} + 1.14 \cdot 10^{-4}\dot{\omega}^2 + 7.28 \cdot 10^{-11}\dot{\omega}^3 + \tilde{g}(h),$$

(3)

where the dimension of the moment $\tilde{M}$ - «kg*м», and the rotational speed $\omega$ - «min».

Despite its little value, we can’t ignore the parameter $f = 7.28 \cdot 10^{-11}$ because it brings a significant correction to the overall result at the beginning of the acceleration section, where the acceleration is large and the moment is small. Parameters $a, b, g$ could be found from the equations

$$\tilde{a}(h) = 1.21 \cdot 10^{-3}h^2 + 2.69 \cdot 10^{-3}h + 1.08,$$

(4)

$$\tilde{b}(h) = 1.15 \cdot 10^{-4}h^2 - 1.89 \cdot 10^{-1}h + 1.82,$$

(5)

$$\tilde{g}(h) = 2.11 \cdot 10^{-4}h^2 - 2.22 \cdot 10^{-3}h + 1.46,$$

(6)

where the dimension of drilling depth $h$ – «м».

4. Discussion

The results were analyzed by comparing the initial experimental dependencies of the torque and the calculated dependences of the approximating moment (3), received from the coefficients obtained through the approximating dependences (4), (5), (6).
To quantify the quality of the approximation, we used the relative error introduced as the standard deviation of the approximating moment from the initial moment:

\[ E_{rel} = \frac{1}{N} \sum_{i=1}^{N} \left( \frac{\bar{M}_i - \bar{M}_i}{\bar{M}_i} \right)^2 \]  

(7)

The analysis showed that at those specific drilling depths for which the values of the parameters \(a, b, g\) were calculated before obtaining the approximation equations (4), (5), (6), the coincidence of the calculated dependences with the experimental ones is very good. The relative error is literally a few percent. This is illustrated on Figure 5.

If we use the dependences (4), (5), (6) and carry out the analysis at arbitrary depths of drilling, then the accuracy of the obtained results decreases. For example, figures 6, 7, 8 for three sections of arbitrarily chosen depths \(h = 790\) m, \(h = 1440\) m, \(h = 2120\) m show the corresponding illustrations of the analysis results.

**Figure 5.** A comparison of approximating moment with initial moment at the depth \(h=3200\) m.

**Figure 6.** A comparison of approximating moment with initial moment at the depth \(h=790\) m.

**Figure 7.** A comparison of approximating moment with initial moment at the depth \(h=1440\) m.

**Figure 8.** A comparison of approximating moment with initial moment at the depth \(h=2120\) m.
The values of the specified error for the three considered sections at depths $h = 790\, \text{m}$, $h = 1440\, \text{m}$, $h = 2120\, \text{m}$ equal respectively $\hat{E}_{\text{rel}} = 19\%$, $\hat{E}_{\text{rel}} = 25\%$, $\hat{E}_{\text{rel}} = 14\%$.

More details of the research results are presented in [15].

5. Conclusion

We advise researchers to use digital data of completed production processes on modern machines equipped with electronic parameter monitoring systems. This data can be used to solve many engineering problems, including building of new dynamic models of systems-machines, opening the way to the construction of digital twins of complex technology.

With the help of such monitoring systems, we developed and tested a method for constructing empirical differential dependencies for the “Working Body – Environment” machine link on the example of the acceleration mode of drilling tools for drilling rigs with top drive systems. The torque on the drill string during start-up and acceleration of the drive depends not only on the rotational speed and depth of drilling associated with the rock strength, but also on the acceleration of rotation. According to the proposed method, we can construct mathematical models of dynamic processes of other modern machines.

The resulting mathematical dependencies can be used in mathematical models of drilling rigs to simulate the dynamic processes of the drives and their control systems. Created data archives allow us to build mathematical models of other dynamic processes of drilling rigs.

References

[1] Balovnev V I 1981 Modelirovanie protsessov vzaimodeystviya so sredoy rabochih organov dorozho-stroitelnyh mashin - M : Vysshaya shkola, – 335
[2] Y G Berengard and M M Gaytsgori, E Y 1980 Malinovskiy Raschet i proektirovanie stroitelnyh i dorozhochnyh mashin na EVM/ Pod red E Y Malinovskogo – M : Mashinostroenie, - 216
[3] I I Bazhin, YU G Berengard and M M Gaytsgori i dr 1988 Avtomatizirovannoe proektirovanie mashinostroitelnogo gidropridvoda– M : Mashinostroenie, – 312
[4] Ashcheulov A V 2007 Metodologiya proektirovaniya gidravlicheskikh podemnych mehanizmov razvodnyh mostov// dissertatsiya na soiskanje uchenoy stepeni doktora tekhnicheskikh nauk/ Sant-Peterburskij politeknicheskij universitet Sankt-Peterburg
[5] Vetrov Y A 1971 Rezanie gruntov zemleroynymi mashinami - M : Mashinostroenie– 360
[6] Zelenin A N 1968 Osnovy razrusheniya gruntov mekanicheskimi sposobami - M : Mashinostroenie, – 376
[7] Bulatov A I , Proselkov Y M and SHamanov S A 2003 Tekhnika i tehnologiya bureniya neftyanyh i gazovych skvazhin: Ucheb dlya vuzov – M : OOO «Nedra-Biznessentro» – 1007
[8] Berestov E I 2008 Soprotivlenie gruntov rezaniyu: monografiya Mogilev: Belorus - Ros Un-t, – 179
[9] Ashcheulov A V , SHestopalov A A , Horoshanskiy A E and Kochetkov A V 2015 Osobennosti raboty burovyh ustanovok s sistemoy verhnego privoda // Mezhdunarodnyy nauchno-teknicheskiy zhurnal «Himicheskoe i neftegazovoe mashinostroenie» - M: 2, 14-7
[10] A V Ashcheulov, A A SHestopalov and A A Lobachev 2016 Analiz dinamicheskoy nagruzhnosti silovogo verhnego privoda burovyh ustanovok Himicheskoie i neftegazovoe mashinostroenie: Moskva, 3 12-5
[11] Ashcheulov A V 2016 Optimization of Regulator Parameters of the Automatic Regulation System of the Rotation Frequency of the Valve Engine of the Top Drive System of Bore Installation International Journal of Applied Engineering Research 11(22) 11055-9
[12] Sozdanie ekonomichnogo verhnego elektroprivoda dlya mobilnyh burovyh ustanovok: otchet o PNI v 5 tomah / FGAOU VO SPbPU; lead: Ashcheulov A V SPb , 2014-2017 – GR114110570105
[13] TSuprikov A A, CHerednichenko V G, Kritskaya V G and Kritskaya L M 2011 Analiz protsessa razrusheniya porody dolotom pri burenii skvazhin Nauchnyy zhurnal KubGAU, 74(10)

[14] J A Nelder and R Mead 1965, Computer Journal, 7

[15] Lobachev A A 2017 Issledovanie nagruzhennosti elementov reduktora sistemy verhnego privoda/ dissertatsiya na soiskanie uchenoy stepeni kandidata tekhnicheskikh nauk po spetsialnosti 05 02 02/ Sankt-Peterburgskiy politekhicheskiy universitet Petra Velikogo Sankt-Peterburg