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A Method for Applying the Use of a Smart 4 Controller for the Assessment of Drill String Bottom-Part Vibrations and Shock Loads

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Abstract: Optimization of drilling processes for oil and gas and geothermal wells requires the effective use of mechanical energy for the destruction of rocks. When constructing a well, an important indicator of the drilling stage is the mechanical speed. Therefore, when performing drilling operations, operators usually use blade bits of an aggressive design and often use forced drilling modes. Drill bits under forced operation modes generate a wide range of vibrations in the drilling tools; in turn, a drill string, being a long-dimensional deformable body, causes the development, amplification, and interconnection of vibrations of different types. Vibration loads reduce the technical and economic indicators of drilling, with destructive effects on drill string elements, and cause complications and emergencies. The authors initiated the creation of an informational and analytical database on emergency situations that occurred as a result of excessive vibrations of the drill string during the construction of deep wells in the deposits of the Dnipro–Donetsk Basin. For the first time, the suitability and effectiveness of using the Smart 4 controller ("Innova Power Solutions", Calgary, Canada) for monitoring the vibration load of the drilling tool was tested in industrial conditions, while the controller was used as a separate element in the drill string. A special module was developed for the reliable installation of the Smart 4 controller, with a power battery in the layout of the lower part of the drill string. During the testing of the proposed device for measuring vibrations in the process of drilling an inclined well, verification of the registered data was carried out with the help of a high-cost telemetry system. The implementation of the proposed innovation will allow each operator to assess the significance of the impact of vibrations and shocks on the production process and, if necessary, adjust the drilling modes or apply vibration protection devices. In addition, service departments that operate and repair drilling equipment will be able to obtain an evidence base for resolving warranty disputes or claims.

Keywords: drill string vibrations; shock loads; sensor; bit; positive displacement motor; drilling tool

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1. Introduction

In the process of drilling oil and gas and geothermal wells, the drill bit, which destroys rocks, can generate a wide range of drilling tool vibrations [1–3]. When using a drill string to carry out the drilling process, phenomena that are characteristic of classic elastic rods often occur in its sections. In particular, the string can experience local loss of stability; it can deform, acquiring a spiral shape; accumulate and then release the potential energy of elastic deformation; or carry out longitudinal, transverse and torsional oscillations [4–6]. In general, the drill string is a long-dimensional deformable body that, under certain conditions, can cause the development, amplification, and interrelationship of vibrations of different classes [7–9]. When drilling a well and drilling under a conductor, operators can very often visually observe a significant vibration of the lead pipe. As the depth of the well increases, the drilling tool near the hole continues to experience dynamic loads but without visible manifestations of vibration at the daylight surface.

Intense vibrations significantly reduce the technical and economic indicators of drilling; they destructively affect the elements of drill strings, bits, downhole engines, increase the specific energy consumption of the drilling process, and cause off-duty and emergency situations, which ultimately lead to an increase in financial costs for drilling each meter of the well [10–12]. A trivial solution to the problem is to reduce the rotation speed of the drilling tool and reduce the axial load on the bit. Such actions usually make it possible to reduce vibration loads to the permissible limit, but at the same time, the mechanical speed of drilling is lost [13,14]. Another, more effective way to solve the problem of the harmful effects of vibrations in drilling is based on the use of special vibration protection devices [15–17]. Among them, the most popular are drilling shock absorbers [18–21], dynamic single- and multi-mass vibration dampers [22,23], and specialized dampers with a high bearing capacity [24–27]. Similar anti-vibration devices, which prevent the occurrence of excessive dynamic loads, are often used in oil fields during the extraction of hydrocarbons by deep pumps [28,29]. For the effective use of these means of vibration protection for the drill string, high-quality flushing of the well should be ensured [30,31], and the surfaces of the steel parts of the shock absorbers, which are actively in contact with the abrasive, should be protected with functional coatings [32–35]. Also, issues related to early failure, loss of tightness, and the inadvertent self-loosening of threaded connections as a result of exposure to high vibrations should receive special attention [36–38].

The motivation for conducting this study was a number of real industrial complications and emergencies, the solution of which the authors of the article took a direct part in. When constructing the well, the main indicator of the drilling stage is mechanical speed, because the time for a complete cycle and the cost of constructing a well depend significantly on it. Today, during drilling operations in the deposits of the Dnipro–Donetsk Basin (Ukraine), in order to obtain high technical and economic indicators, drilling operators use blade bits of an aggressive design and apply forced drilling modes. As field studies have shown, uncontrolled cutting depths and stratified rocks with sharply changing characteristics very often lead to instant stops or jamming of such reaches. The most characteristic data on the occurrence of emergencies during drilling in the deposits of the Dnipro–Donetsk Basin were selected and are presented in Table 1. The presented information is taken from the "Accident Investigation Acts" compiled by a group of drilling and service companies. Some industrial cases noted in this table will be discussed and analyzed in more detail in the next section of the article. The main mistakes that led to complications in the drilling process were the incorrect selection of the layout of the drill string bottomhole assembly (BHA), the selection of an irrational drilling mode, and ignoring the use of anti-vibration devices. Drill string failures occurred due to overloading, excessive vibrations, or load fluctuations. Vibrations and cyclic loads mainly led to fatigue failure and loosening of the drill bit, while overloading the equipment caused loss of element stability, failure due to high contact stresses, or the phenomenon of material flow and rupture.

According to the data in Table 1, it is possible to distinguish the age of the rocks and the diameter of the bit, which caused complications in the drilling operations. The largest share of emergencies fell within the Triassic system (T) and the upper stage of the Carboniferous system (C3), which represents 62.5% and 18.75% of all the cases considered in the table. On the other hand, when drilling in the Cretaceous system (K), Jurassic system (J) and Serpukhovian stage of the Carboniferous system (C1s2), emergencies rarely occurred. Regarding the diameter of the bits, 50% of the abnormal cases happened with bits with a diameter of 444.5 mm, and 31.25% with bits with a diameter of 295.3 mm. To solve the described problem, an initiative has been proposed, which consists in conducting field research on the causes of emergencies caused by the BHA component integrity violation.

The main goal of this initiative is to collect industrial data on the nature and magnitude of downhole vibrations and to provide recommendations on optimizing drilling modes and the correct choice of BHA layout.

Table 1. Cases of emergencies in the Dnipro–Donetsk Basin fields.

No	Drilling Depth, m	Stratigraphy	Place of Tool Damage	Type of Drill Bit	Diameter of the Bit, mm	Diameter of the Drilling Tool, mm	Axial Load on the Bit, kN	Rotational Frequency of the Upper Power Drive, rpm
1	1009	K	Adapter	GT55Cs	393.70	241.30	120	60
2	1420	J	PDM *	X616S	444.50	241.30	70	30
3	2656	T	PDM	GS1915T	444.50	241.30	80	55
4	2293	T	PDM	SI 516 HBPX	295.30	203.2	140	40
5	2686	T	PDM	VS616	444.50	241.30	40–80	20–40
6	2067	T	PDM	SDI519MHBPX	393.70	241.30	160	30–40
7	2286	T	PDM	D516M HPX	295.30	203.2	50–80	90
8	1695	T	Shock absorber	TCTi + CR	444.50	241.30	60–80	120
9	1688	T	PDM	MSi619LHEBPX	444.50	241.30	60–110	20
10	1752	T	PDM	8D31516HBPX	295.30	203.2	100	50
11	1977	T	PDM	U519S	444.50	241.30	100	40
12	2372	T	PDM	VS616DGHXU	444.50	241.30	160	55
13	2558	C3	PDM	U519S	311.15	203.2	120	40
14	2971	C3	PDM	XR + C	295.30	203.2	90	40
15	2679	C3	PDM	CDi619VHBPX	444.50	241.30	60–80	45–50
16	4375	C1s2	PDM	Z516S	295.30	203.2	60	50

* PDM—positive displacement motor.

Machines, mechanisms, and devices that are equipped with various types of sensors and sensors are quite widely used in various fields of science and technology [39–41]. A number of critical infrastructure elements, such as oil and gas and energy facilities [42–44], as well as a number of critically important programs related to the use of a smart network, the Internet of Things, etc., cannot function properly without the participation of modern sensor components [45,46]. Today, the level of available technologies allows pothole vibrations to be measured using independent pothole sensors [47–49]. According to the principle of operation, such devices can be divided into two types: those that record data into the memory system and those that transmit a signal to the daylight surface in real time [50–53].

Recent studies have extensively investigated the dynamics of drill string vibrations and shock loads, emphasizing the critical role of sensor technology in this area [54]. Researchers have explored various types of sensors, including accelerometers, strain gauges, and fiber optic sensors, to monitor the behavior of drill strings in real time. For instance, several works [55,56] highlight the effectiveness of accelerometers in detecting vibration patterns that indicate potential failures in drilling operations. The development of wireless sensor networks allows for the real-time transmission of data from remote drilling sites, facilitating immediate analysis and decision-making. Research studies [57,58] have demonstrated how integrating wireless sensors with advanced telemetry systems can optimize drilling parameters by providing continuous feedback on operational conditions. Additionally, innovations in miniaturization and energy harvesting have made it feasible to deploy sensors in challenging environments, ensuring that data collection is both comprehensive and reliable [59]. The practical applications of sensor technology in drilling operations are numerous. Case studies, such as those conducted by the study in [60], illustrate how the real-time monitoring of vibrations and shock loads can lead to proactive maintenance strategies, reducing the risk of equipment failure. Machine learning algorithms and signal processing methods are increasingly employed to analyze complex datasets generated by sensors. Research by [61–63] highlights the potential of machine learning models to predict drill string failures based on vibration patterns, allowing for timely interventions.

The most advanced sensors transmit data during drilling to the daylight surface for a prompt response to changes in the drill string dynamic operating mode [64,65]. Real-time data transmission can be carried out by an electromagnetic channel (in this case, with a depth limitation) or a hydraulic communication channel (in this case, the quality of the drilling fluid, pumping group, and hydraulic system of the drilling rig has a significant impact on the transmission of the signal). For the customer of drilling works, the use of this type of equipment has one drawback—it increases the overall cost of the service. Therefore, in the oil and gas market of Ukraine, customers mostly refuse to use the described complex equipment.

Since we are trying to introduce technology and make it available to every customer in the Ukrainian market, we focus on the sensor that records the data and saves them in the memory system. Such data, obtained from the device's memory, can be compared with the events that occurred during drilling and with the performance of the equipment to increase the efficiency of drilling and to prevent complications. In the process of choosing an autonomous module, our attention was drawn to the Smart 4 technology presented by Innova Power Solutions. The main business of the company is the production of high-temperature lithium batteries for telemetry systems and sensors of various types. Starting in 2008, such batteries were equipped with Smart 2 and Smart 3 battery health monitors ("Innova Power Solutions", Calgary, Canada), which recorded temperature, residual current, and voltage. Since 2015, the technology of the controller has been improved to Smart 4, which is equipped with a three-axis accelerometer for recording shocks and vibrations [66–68]. The latest version of the controller includes gyroscopes that can measure the rotation frequency of the punching tool and capture the stick–slip phenomenon. According to the authors, this is the most interesting technology for implementation on the Ukrainian market, as it is the most affordable, and in terms of accuracy and frequency of data registration, it is not inferior to much more expensive analogs. However, the Smart 4 controller technology was developed to monitor the condition of lithium batteries and needs to be adapted in order to be used to register the dynamic mode of operation of the bottom of the drill string.

Our research aims to achieve the following:

- Analyze the typical examples of complications and emergencies that occurred during drilling operations in the deposits of the Dnipro–Donetsk Basin that are related to the dynamic operation mode of the of the drill string bottom part;
- Develop a module for using the selected sensor with a three-axis accelerometer and a gyroscope for recording shocks and vibrations at the lower part of the drill string and implement industrial approval of the proposed device.

Concluding the introductory section, we would like to note that the implementation of the proposed technology would provide an opportunity for each operator to assess the severity of the impact of vibrations and shocks when drilling deep oil and gas and geothermal wells and to compare the obtained data with critical events that occur during drilling. Service centers and service departments engaged in the operation and repair of drilling equipment will be able to obtain an evidence base for resolving warranty disputes or claims.

2. Materials and Methods

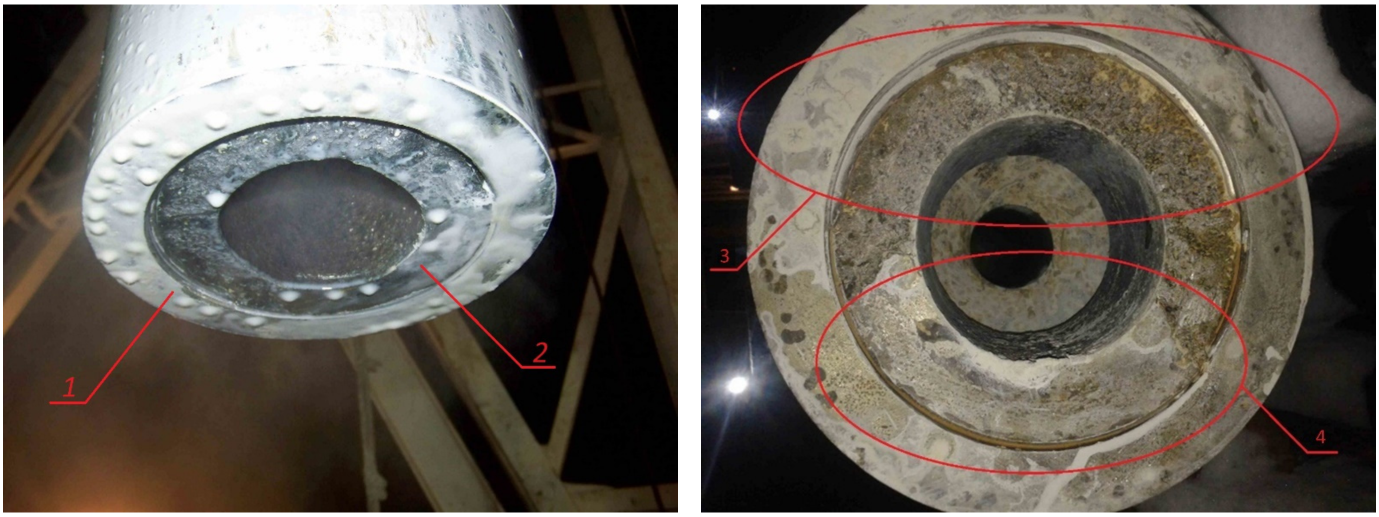
2.1. Case Reports of the Vibration Impact on the BHA Elements That Caused Complications or Emergencies

In an attempt to increase the mechanical speed of drilling and minimize equipment costs, customers who rent drilling tools and PDMs from service centers often violate the provided equipment operation recommendations (i.e., they do not ensure that they use the proper BHA equipment, they exceed the recommended rotation frequency of the tool and axial load on the bit, they ignore the application anti-vibration devices, etc.). Such actions lead to the emergence of complications and emergencies in the drilling process, as well as guarantee disputes if there is equipment damage. Therefore, service centers are interested in the development and implementation of an inexpensive controller for recording the real drilling modes in which the drill string is operated.

2.1.1. Effect of Transverse Vibrations

A PDC GT55Cs bit manufactured by the Halliburton company (Duncan, Oklahoma, USA) was used when drilling rocks of the Cretaceous system at one of the deposits in the Dnipro–Donetsk Basin. A shock absorber and a hydraulic pump were included in the BHA scheme. To isolate the PDM spindle section from axial vibrations, the customer decided to install the shock absorber below the motor, but no compromise was reached regarding the selection of the number and diameter of the support-centering elements. The following BHA scheme was used: 15 ½ Bit GT55Cs (0.48 m) + Crossover sub (0.38 m) + 9 ½ Shock Tool (4.3 m) + Crossover sub (0.28 m) + 9 ½ Drilling motor (10.55 m) + Crossover sub (0.35 m) + 15 ½ String Stabilizer (1.35 m) + 9 Drill Collar (17.65 m) + 15 ½ String Stabilizer (1.35 m) + 8 Drill Collar (24.07 m) + Crossover sub (0.45 m) + 8 Jar (5.39 m) + Crossover sub (0.44 m) + 8 Drill Collar (51.08 m) + Crossover sub (0.33 m) + 5 Drill Pipe (to surface).

During drilling at a depth of 1009 m, the pressure in the well flushing system decreased, and the mechanical speed of drilling decreased to zero. After lifting the tool, a fracture of the threaded nipple of the adapter between the PDM and the at-bit shock absorber was discovered (Figure 1a).



(**a**) (**b**)

Figure 1. The case of the destruction of the threaded nipple of the adapter between the PDM and the at-bit shock absorber: (**a**) View of the destroyed element of the drill string immediately after lifting from the well; (**b**) A detailed inspection of the place of damage to the tool; 1—the thrust end of the threaded coupling; 2—part of the adapter's nipple; 3—zone of fracture, 4—zone of crack formation and propagation.

Attention should be paid to the peculiar nature of the adapter nipple fracture (Figure 1b). Here, two separate zones of material destruction can be distinguished: zone 4 is a flat, smooth, polished surface where a fatigue crack has formed and grown; and zone 3 is a coarse-grained surface, which is a zone of sudden fracture.

The main reasons of the described complication are the insufficient stabilization of the BHA bottom part, partially the lack of a body stabilizer on the PDM and too-high rigidity at the part of the layout above the motor, since full-size calibrators were used. In the applied BHA, the distance from the bit to the lower calibrator was 15.5 m, which is essentially a pendulum scheme. The lack of a centering element on the PDM housing led to the formation of excessive deflections on the shock absorber and the PDM, which were subjected to cyclic loads of alternating signs during drilling. The use of two full-size calibrators above the motor limited the area of propagation of transverse vibrations, so the vibrations were concentrated in the area of the punching tools. The adapter between the shock absorber and the PDM was the most stressed, in which a fatigue crack formed under the action of transverse vibrations, which ultimately led to its destruction.

Analysis of the dynamics of the considered BHA was carried out using the specialized Halliburton (Duncan, OK, USA) software product, Wellplan-Software (version 5000.14.0) [69]. Figure 2a shows the dependence of the maximum bending moment in the drill string on the speed of the tool rotation (here, drilling was carried out in a combined way: a maximum of 99 rpm was provided by the PDM, and the rotor was used to increase the speed). Note that the *z*-axis is directed along the axis of the drill string, and the x- and y-axes are the main central axes of the cross-section of the string. One can see on this graph that at a rotation speed of around 162 rpm, there was a sharp disturbance of the bending moment, which reached more than 45 kNm. At the same time, Figure 2b illustrates that at a safe drilling speed, the maximum bending moment in any of the sections of the column did not exceed 10 kNm (the maximum value was registered in the area of the threaded adapter between the hydraulic cylinder and the shock absorber). In fact, the forced mode of drilling led to the occurrence of an excessive bending moment, which ultimately caused the emergency.

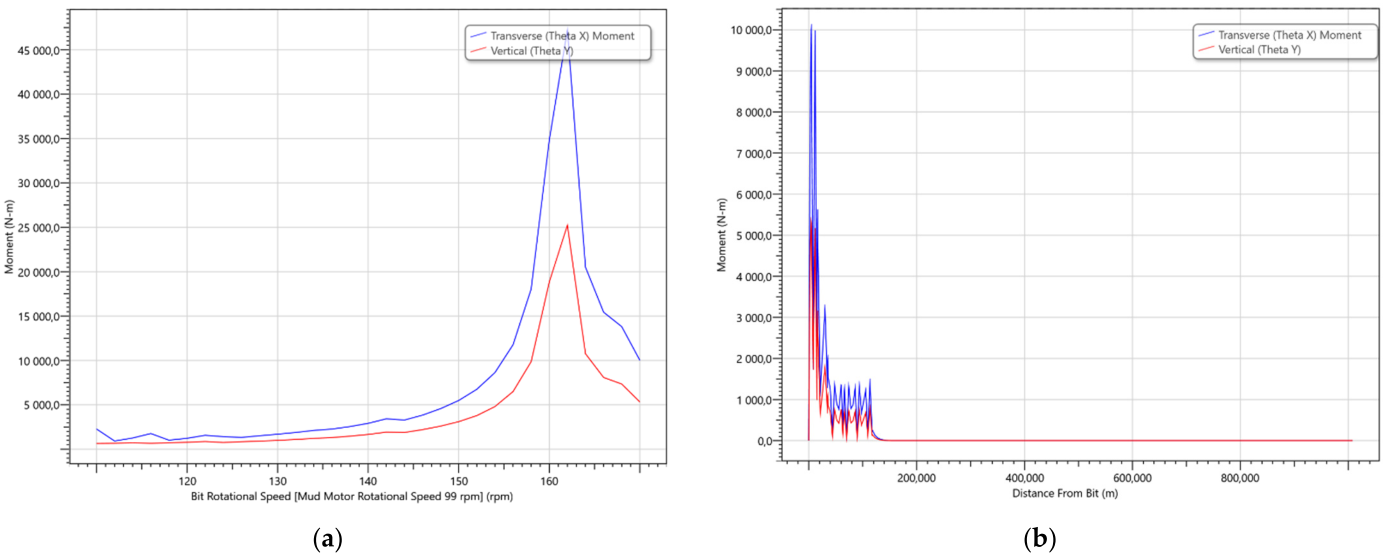


Figure 2. Bending moments in the drill string: (**a**) Dependence of the maximum bending moment on the rotation speed of the drill string; (**b**) Distribution of the maximum bending moment along the length of the column at a rotation speed of 153 rpm.

With regard to the considered complication, we note that a similar BHA, in which a drilling shock absorber was installed under the PDM while, at the same time, the motor body was equipped with an undersized centerer and calibrators were also used with a diameter smaller than the nominal diameter of the bit, successfully worked in the deposits of the Dnipro–Donetsk Basin.

2.1.2. Effect of Axial Vibrations

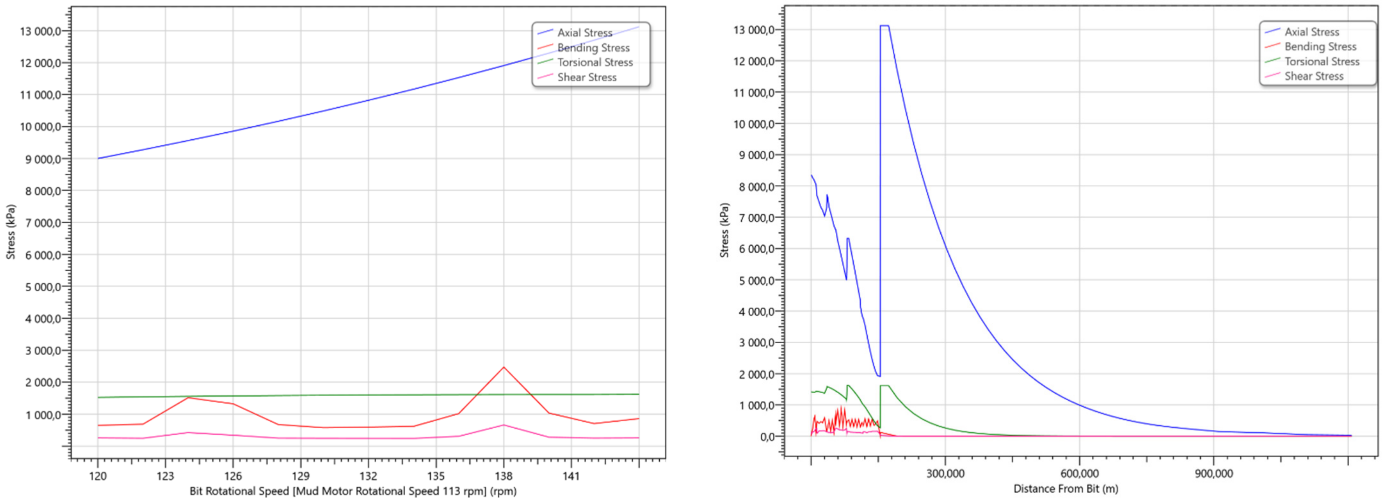
When drilling rocks of the Cretaceous and Jurassic systems in the range of 315–1208 m (for a technical column with a diameter of 340 mm), a BHA with a PDM and an over-bit shock absorber and a Smith SDGH roller bit was used (the shock absorber was installed above the engine). Actually, for vibration isolation of the drill string from axial vibrations, which are formed during the drilling of heterogeneous rocks of the upper sections, the shock absorber was included in the composition of the BHA. The following arrangement of the BHA was used: 17 ½ Bit (0.55 m)+ 9 ½ Drilling Motor (10.5 m) + 17 3/8 String Stabilizer (2.43 m)+ 9 ½ Drill Collar (8.2 m) + 9 ½ Shock Tool (3.75 m) + 9 ½ Drill Collar (9.22 m) + Crossover sub (0.73 m) + 15 3/8 String Stabilizer (0.96 m) + 9 Drill Collar (18.28 m) + 15 3/8 String Stabilizer (0.94 m) + 9 Drill Collar (23.27 m) + 15 ¼ String Stabilizer (0.96 m) + Crossover sub (0.45 m) + 8 Drill Collar (29.73 m) + Crossover sub (0.6 m) + 8 Drilling Jar (5.41 m) + Crossover sub (0.43 m) + 8 Drill Collar (37.77 m) + Crossover sub (0.43 m) + 5 ½ Drill Pipe (to surface).

The use of the shock absorber allowed the customer to create an axial load on the bit of up to 18 tons to obtain the maximum drilling speed without axial vibrations of the drill string being visible at the day surface. After reaching the design depth of the casing column, the drilling tool was lifted, and excessive axial backlash was found—40 mm on the spindle section of the gas turbine engine (with an allowable value of no more than 2 mm). When disassembling the PDM, the destruction of the thrust-bearing separators and mechanical damage to the internal elements of the spindle section of the PDM were found (Figure 3).

(a) (b)

Figure 3. Damage to thrust-bearing separators and internal elements of the spindle section of the screw engine: (**a**) Damaged elements of the downhole motor; (**b**) Inspection of the spindle part of the downhole motor; 1 and 2—upper and lower bearing brackets; 3 and 4—bearing rollers, 5—PDM bearing housing.

Such damage is caused by the excessive impact of axial vibrations on the bearing support of the engine and the high contact stresses that occur during the dynamic contact interaction between the support elements. Since the shock absorber was installed above the PDM, the thrust bearings of the spindle section turned out to be unprotected from vibration loads. In general, during the drilling of the Cretaceous, Jurassic, and Triassic systems with ball bits in the oil and gas fields of the Dnipro–Donetsk Basin, significant axial oscillations were observed at the wellhead when an axial load of more than 10 tons was created. In the case under consideration, an axial load of up to 18 tons was used on the bit; at the same time, there were no vibrations of the drill string and the oil system at the day surface, and no danger was visually observed (the shock absorber was activated above the PDM). Using the specialized software package "Halliburton: Wellplan-Software (version 5000.14.0)" [69], the stresses that arose in the BHA elements were analyzed. The graphs (Figure 4a) show the dependence of the maximum stresses in the drill string on the rotation speed. Figure 4b illustrates the distribution of stresses along the length of the column at the maximum rotation frequency of 144 rpm. It should be noted that the stresses on the graphs did not exceed the limit values; however, vibration loads at a high speed of rotation of the tool led to high dynamic contact stresses and caused damage to the PDM thrust bearing.



(**a**) (**b**)

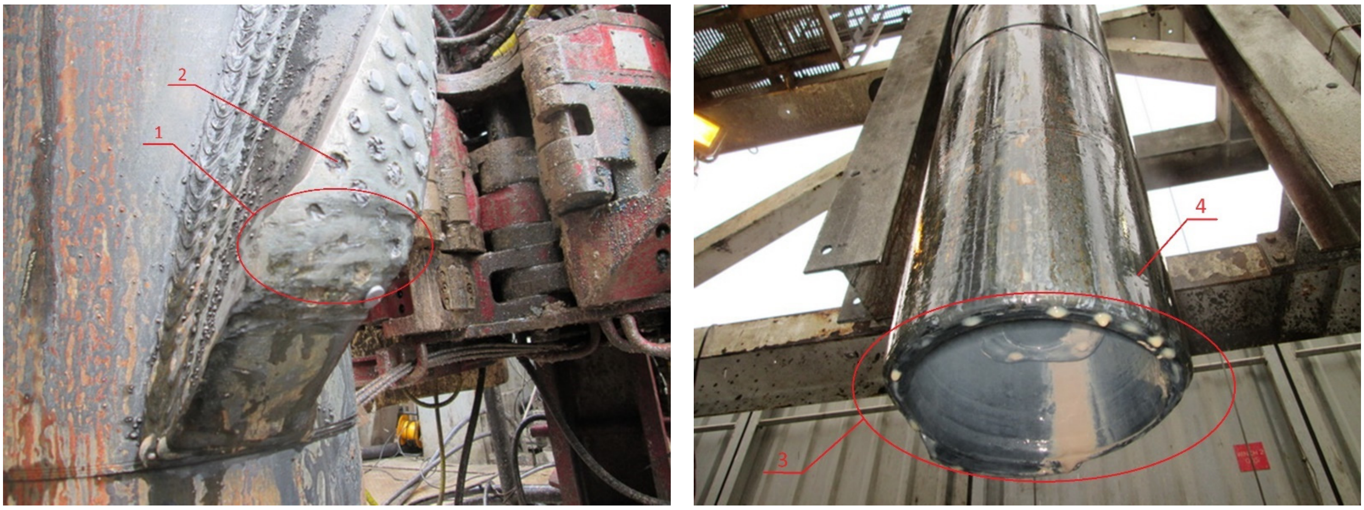
Figure 4. Stresses in the elements of the drill string: (**a**) Dependence of the maximum stresses on the rotation speed of the drill string; (**b**) Stress distribution along the length of the column at a rotation speed of 144 rpm.

For the considered type of BHA, it is recommended to use a low-speed PDM for the possibility of reducing the rotation frequency of the bit from 145 rpm to 110 rpm. In order to ensure maximum drilling efficiency, to protect against the vibrations of the internal combustion engine, and to increase the duration of the trip, it is necessary to install a drilling shock absorber directly above the bit.

2.1.3. Effect of the Whirling Movement of Drilling Tools

A PDC Smith MSi619LHEBPX bit (Ackerman drilling services, Houston, TX, USA) and a 241 mm diameter rotary screw motor were used to drill the Triassic system in the interval of 1273–1688 m in one of the wells in the Dnipro–Donetsk Basin. A thick layer of sandy-clay soils with the inclusion of conglomerates and rocks prone to erosion and shedding represented the geological section in this interval. The following BHA was used for drilling: 17 ½ Drill Bit (0.63 m) + 17 ½ Dog Sub (0.60 m) + 9 ½ Drilling motor (10.20 m) + 17 ½ String Stabilizer (1.69 m) + 10 Drill Collar (8.18 m) + Crossover sub (0.44 m) + 9 ½ Shock Tool (3.29 m) + Crossover sub (0.4 m) + 10 Drill Collar (8.19 m) + 17 ½ String Stabilizer (1.69 m) + 10 Drill Collar (16.48 m) + 16 3/8 String Stabilizer (1.69 m) + 10 Drill Collar (8.30 m) + 9 Drill Collar (9.40 m) + Crossover sub (0.40 m) + 8 Drill Collar (18.82 m) + 8 Jar (9.7 m) + 8 Drill Collar (37.53 m) + Crossover sub (0.43 m) + 5 HWDP (56.30 m) + Crossover sub (0.39 m) + 5 ½ Drill Pipe (to surface).

When the bottomhole was at a depth of 1688 m, a cyclical change (increase–decrease) of the torque began in the range from 6 to 22 kNm with a constant axial load on the bit. This process was accompanied by a rapid increase in the pressure of the washing liquid in the injection line in the range from 1.5 to 3.5 MPa. Every time the torque increased, the operator performed a smooth separation of the bit from the surface of the hole and started drilling again. During the next restoration of circulation after the bit was detached from the hole, a decrease in the idle pressure of the PDM by 1.5 MPa was recorded. A decision was made to raise the BHA for revision by the PDM. During the revision of the tool, a break in the spindle part of the PDM, destruction of the arms on the lower edges of the calibrator blades, and a partial loss of the diameter of the lower calibrator were found (Figure 5).

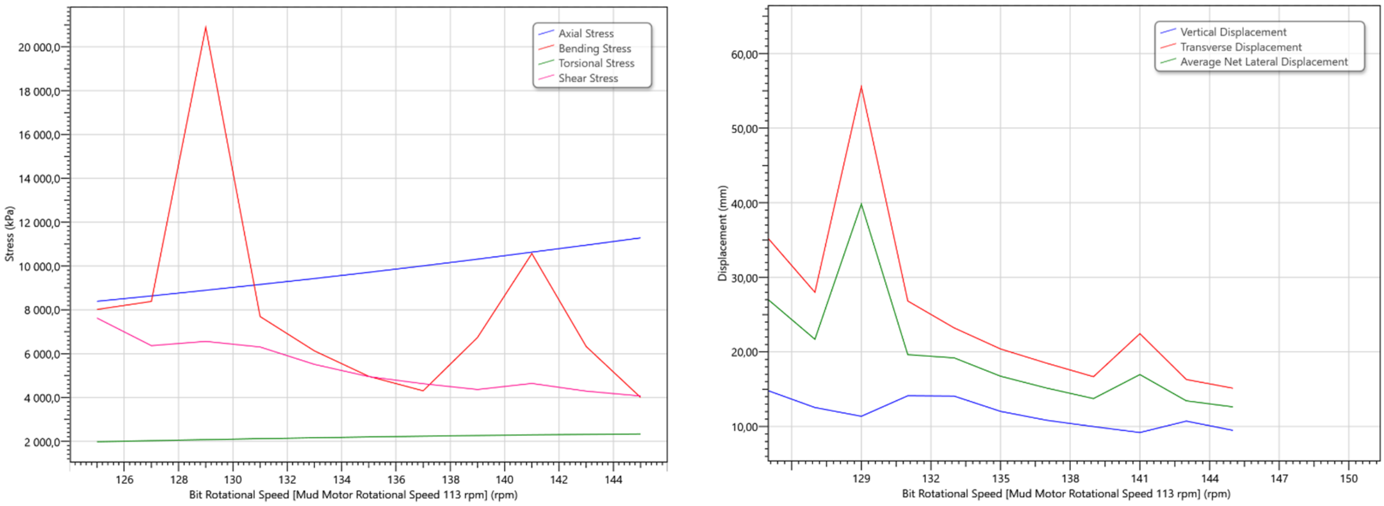


(**a**) (**b**)

Figure 5. Breakage of the spindle part of the PDM due to the whirling movement of the drilling tool: (**a**) Damaged calibrator blades; (**b**) Detecting a break in the spindle part of a downhole screw motor when lifting a tool; 1—the zone of destruction of the lower edge of the calibrator blade; 2—slivers of the hard alloy armament of the stabilizer; 3—place of breakage of the PDM housing, 4—PDM housing.

Overshots with spiral/collet grabs and 350 and 380 mm diameter feed funnels were used to extract the remaining part of the BHA from the well. The lifting process and analysis of the condition of the emergency (broken) layout provided accurate indications that the actual diameter of the wellbore had exceeded the nominal one by 80%. Taking into account the above, it was concluded that during the drilling of the well, there was a whirling vibration of the BSC, which led to a significant increase in stress in the threaded elements of the PDM, uneven wear of the bit armature and calibrators, and, ultimately, to an emergency situation.

Modeling of the behavior of the considered BHA (Figure 6) indicates a surge of bending stresses and transverse displacements of the drilling tool during the forced drilling mode (the rotation frequency of about 130 rpm is very high for the existing engineering and geological conditions). According to the authors, the formation of vortex oscillations in the considered case is primarily caused by the high cavernousness of the wellbore, as well as non-compliance with the recommended drilling mode. To prevent similar situations when drilling unstable deposits of the Triassic system at this deposit, it is recommended to use a rotary BHA, as well as to include downhole shock absorbers in the drill string for damping longitudinal vibrations (when using rotary bits) and torsional vibrations (when using blade bits).



(**a**) (**b**)

Figure 6. The maximal stresses and displacements in the bottom elements of the drill string: (**a**) Dependence of the maximum stresses on the rotation speed of the drill string; (**b**) Dependence of the maximum movements on the rotation speed of the drill string.

2.1.4. Effect of Torsional Vibrations

During the drilling of a deep well in one of the fields of the Dnipro–Donetsk Basin, a 241 mm diameter drill bit and a Varel VS616DGHXU PDC drill (Varel Energy Solutions, Mexico) bit were used. The deepening took place in the Triassic system in the interval of 2189–2372 m. The rocks were mainly represented by red viscous clays. The following BHA was used: 17 ½ Bit (0.46 m) + 9 ½ Drilling Motor with 17 ¼ sleeve stabilizer (10.63 m) + 17 ¼ String Stabilizer (2.5 m) + 9 ½ Drill Collar (18.15 m) + 17 ¼ String Stabilizer (2.49 m) + 9 ½ Drill Collar (26.89 m) + Crossover sub (0.78 m) + 8 ½ Drill Collar (54.8 m) + 8 Jar (9.6 m) + 8 ¼ Drill Collar (26.98 m) + Crossover sub (0.67 m) + 6 ¾ Drill Collar (26.91 m) + 5 HWDP (55.05 m).

During the trip, the mechanical speed of drilling and the torque were constantly changing, which obviously indicates the layering of rocks. The operator tried to adjust the drilling mode according to the actual situation. At the drilling interval of 2365–2372 m, cyclic pressure increases in the range of 30.0–40.0 MPa began to occur, which were accompanied by stops of the upper power drive and further acceleration of the rotation of the drilling tool clockwise (these are convincing signs of torsional vibrations). With the next increase in pressure in the injection line, the operator performed the traditional procedure of reducing the supply of washing liquid and performing a smooth separation of the bit from the hole in order to prevent the destructive effect of vibration loads. After restoring the circulation of the washing liquid, an increase in the engine idle pressure from 22.5 to 24.5 MPa was noted, with constant performance of the drilling pumps. During further attempts to resume drilling, the absence of a differential drop in the PDM was recorded with an axial load on the bit of up to 8 tons. A decision was made to raise the drilling tool to determine the causes of the complication.

During a visual inspection of the gas turbine engine after lifting the drilling tool, a fracture of the body stabilizer at the place of the transition of the blades into the body as well as a fracture of the threaded nipple of the upper adapter of the angle regulator were detected (Figure 7).

The conclusion of the analysis of the emergency is that the damage was caused by distortion of the stick–slip torsional vibrations. Usually, when the reactive moment is released, the stabilizers are unscrewed, since the rotation of the drill string occurs in the opposite direction to the direction of the thread. In this situation, after the bit was jammed, there was a sharp start of the PDM with high angular acceleration, which led to the attachment of the threaded connection of the stabilizer and, as a result, to the violation of its integrity. According to the authors, the fracture of the threaded connection of the upper adapter of the angle regulator occurred simultaneously with the fracture of the stabilizer under the action of the same dynamic loads. The estimate of the relative angle of twisting of the BHA when a dynamic torque occurs was simulated in the "Halliburton (Duncan, OK, USA): Wellplan-Software (version 5000.14.0)" environment [69] and is presented in Figure 8. In the lower part of the drill string, we observed a disturbance in the angle of rotation of the cross-sections of the string around its longitudinal axis. In particular, the cross-sections of the PDM were turned more than a full revolution relative to the conventionally stationary cross-section of the column.

(**a**) (**b**)

Figure 7. A visual inspection of the damage to the PDM caused by the influence of torsional vibrations: (**a**) Lifting a damaged downhole screw motor; (**b**) Destroyed stabilizer housing; 1—the rotor of the power pair; 2—the place of the fracture of the threaded nipple of the angle regulator adapter; 3, 4—PDM housing; 5—the location of the housing stabilizer fracture; 6—stabilizer blades.

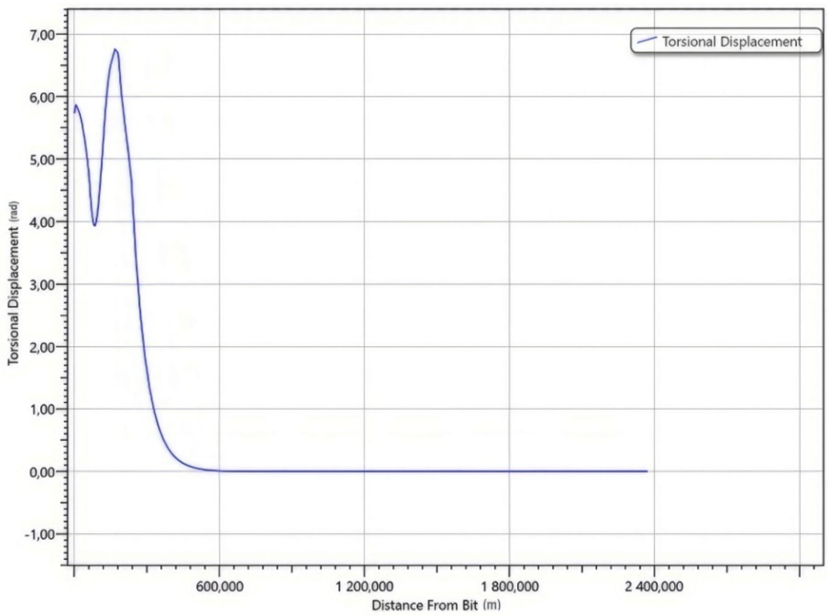


Figure 8. Twisting angles of cross-sections of the lower part of the drill string during complications.

2.2. A Device for Recording Bottomhole Vibrations

The main idea underlying the principle of operation of the sensor for recording bottomhole vibrations is to convert mechanical vibrations into electrical signals, which will then be processed and interpreted. Oscillations are detected using accelerometers and gyroscopes. When the sensor detects vibrations, it generates an electrical signal whose frequency and amplitude depend on the vibration parameters. In other words, the vibration sensor acts as an interface between the mechanical vibrations and the electronic data processing system, which allows useful information to be obtained about the dynamic mode of operation of the drill string.

A compact sensor with a three-axis accelerometer and a gyroscope (Figure 9) will be mounted inside a lithium thionyl chloride battery. The sensor has a very low power consumption and an extended memory capacity, which allows for uninterrupted logging of pitting data over 800–1000 h of operation.

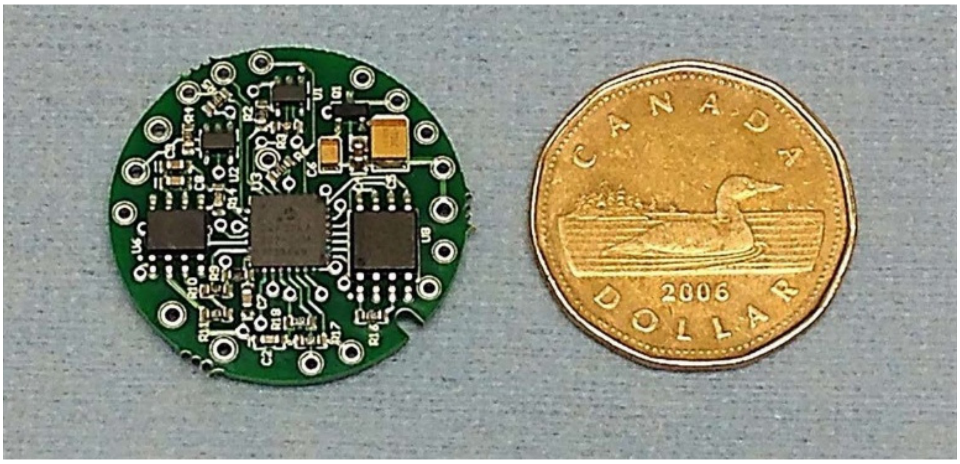


Figure 9. Smart 4 controller for recording the vibrations of the bottom of the drill string (a coin is shown next to the controller for comparative size assessment).

The software product WatsonTM ("Innova Power Solutions", Canada) (Figure 10) is used to read the data, in the interface of which it is possible to change the scale of the curves and graphically visualize various parameters, including the temperature, rotation frequency, vibrations, and shocks along three mutually perpendicular axes [67]. The advantage of this interface is that digital data can also be obtained in a format convenient for further processing and interpretation; for example, they are available not only in the form of diagrams but also in the form of tables with a set of numerical data. The device has its own digital clock and records the event with reference to time. When connecting the controller to the computer, time synchronization occurs, which allows one to get a clearer picture of the pitting data. The device allows one to record the mean square value of the vibrations, as well as longitudinal and transverse vibrations along three axes, and can work at temperatures up to 180 °C. The unit of measurement of vibrations is g, and the frequency of data registration is within 10 s.

The sensor allows you to obtain the value of the amplitude of oscillations, which reflects the maximum deviation or acceleration of the drilling tool. This is an important indicator for determining the intensity of vibrations and their impact on drilling and equipment. It is also possible to analyze the oscillation frequency, which can indicate the source of the vibration. In addition, the sensor allows you to determine whether the oscillations are regular or irregular. Regular fluctuations may indicate problems with the drilling equipment, instability of the drilling process, or other technical problems, while irregular fluctuations may be caused by external factors such as geological features, such as rock stratification or heterogeneous inclusions. The data obtained by the sensor can be compared with the drilling modes, which are recorded 24/7 by the geological and technical research station. Furthermore, these data can be additionally superimposed onto the logs of the geophysical studies of the well to obtain a clear understanding of the influence of all possible factors on the dynamics of the layout of the bottom of the drill string. So, for example, by having a gamma log, one can easily monitor the change in the type of rocks, and profilometry gives an understanding of the actual diameter of the wellbore relative to the nominal one in one or another interval, which has a direct impact on the occurrence of fluctuations during drilling.

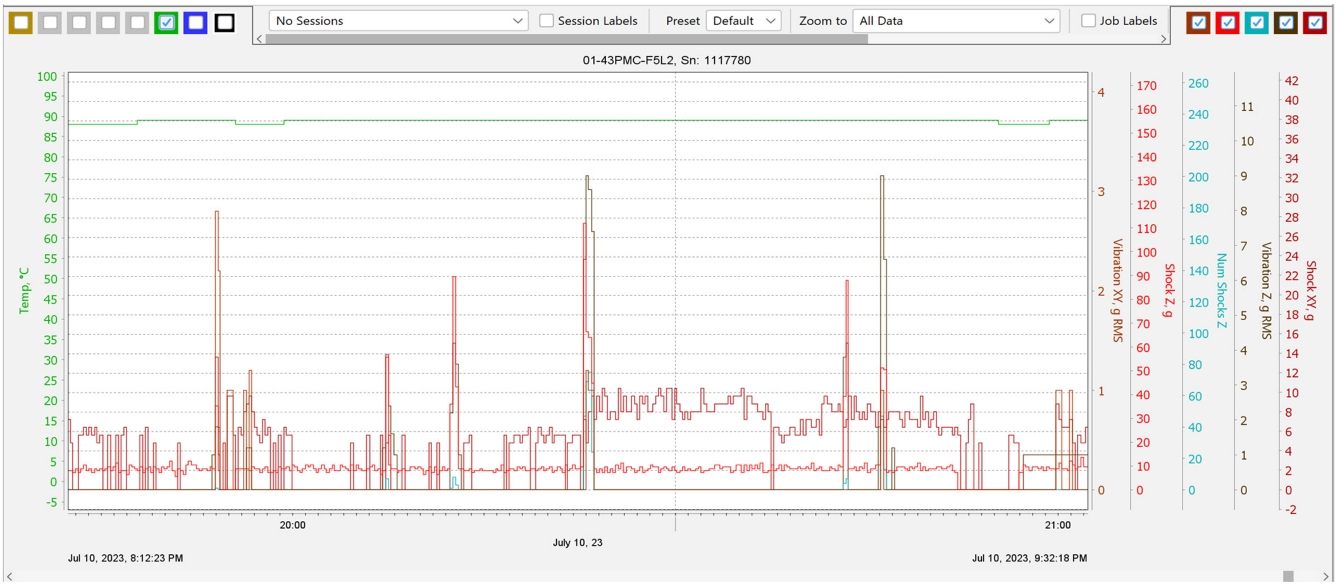
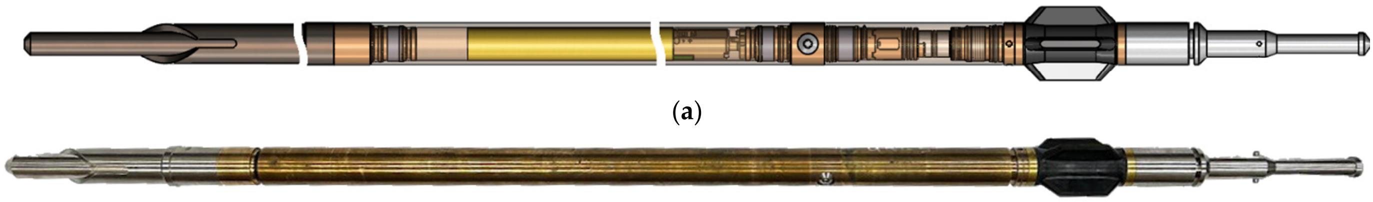


Figure 10. Software product interface for reading data from the controller memory.

2.3. *The Design of the Module for Placing the Vibration Sensor in the Drill String Bottom Part*

An important problem that needs a rational solution is the way of placing the sensor to record vibrations and the power battery in the lower part of the drill string. Extremely limited diameter space and extreme operating conditions significantly complicate this task. Depending on the specific drilling conditions and the requirements for the downhole vibration recording system, its placement can be performed in different ways. Sometimes, sensors are built directly into the diametrical pocket of the drill string wall, or sensors, together with power elements, can be placed in special external modules that are attached to the outer surface of the drill string and have protective casings or shells [1,70]. The study proposes to place the recording device in a specially made module, which is mounted inside the lower part of the drill string. Creating such a module requires attention to design, materials, and the fastening method. The module is specially designed to accommodate the necessary sensor, the lithium thionyl chloride battery, and electronic communications. The module material is resistant to corrosion and abrasive materials, and the module is sealed to protect the electronics from moisture, dirt, and other harmful influences. The module is made as compact and ergonomic as possible to reduce its impact on the drill string diameter and to leave more space for the drilling fluid to flow, and the external shape facilitates the smooth movement of the drilling fluid around the module.

So, for the practical implementation of the ideas outlined above, as well as to avoid the need to use high-cost telemetry systems, a compact module is proposed that includes a Smart 4 vibration sensor and an Innova Power Solutions lithium thionyl chloride battery (Figure 11). A feature of the Smart 4 sensor is its low power consumption, which makes it possible to use a power battery that is three times smaller than the power batteries for traditional telemetry systems.

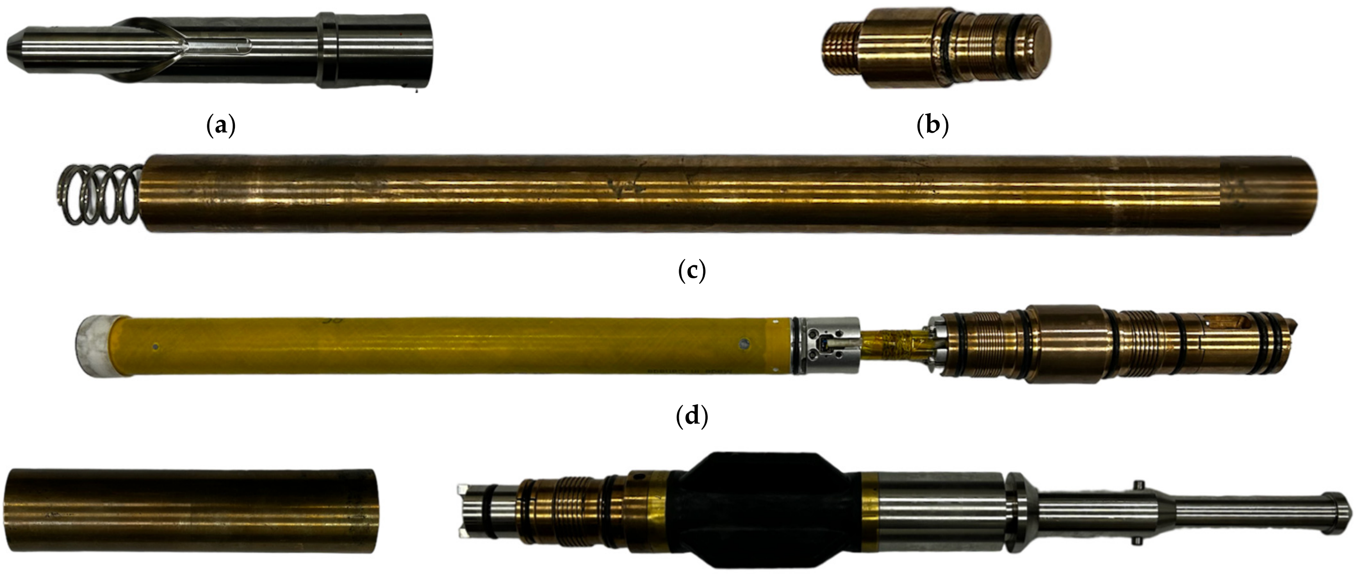


(**a**)

(**b**)

Figure 11. Compact module for installing a vibration sensor and power battery in the BHA: (**a**) Scheme of the module; (**b**) A sample of the assembled module.

Let us take a detailed look at the design and layout of the module from left to right. The guide tip (Figure 12a) is intended for sealing the module and for its landing in the guide sleeve, which is installed in the orienting adapter of the drill string. A two-pin adapter with sealing rings (Figure 12b) is required to connect the guide tip to the main body. The main body of the module (Figure 12c) contains a power element with a Smart 4 controller and a shock-absorbing spring in its inner cavity. The power battery is connected to the housing, which has a ventilation valve, through a support with a built-in cable, which plays the role of an MDM 9/Kintek adapter (Figure 12d). The Kintek connector is fixed with a special fastener and closed with a short upper case. The fishing neck (Figure 12f) is designed to seal the internal cavity of the module, and if necessary, it provides the possibility of lifting the module on a geophysical cable.



(**a**) (**b**)

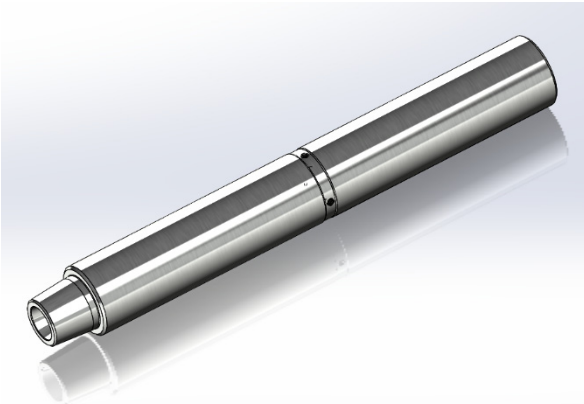
(**c**)

(**d**)

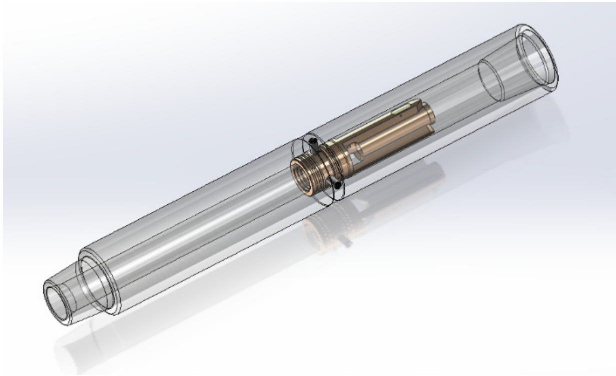
(**e**) (**f**)

Figure 12. Layout diagram of the separate components used in the model assembly: (**a**) Guide tip; (**b**) Two-pin adapter; (**c**) The main body of the module with a shock-absorbing spring; (**d**) Power battery with vibration sensor and battery support; (**e**) The upper body of the contact group; (**f**) fishing neck.

After the module is assembled, it should be placed in the housing elements for its final installation at the bottom of the drill string. For this, it was decided to use a landing adapter (Figure 13a), into which the guide sleeve is installed, and the lower end of the module (guide tip) enters the sleeve itself. The sleeve is fixed with screws so that it does not turn and cannot move in the axial direction (Figure 13b). There is a special wedge in the sleeve, and a groove in the guide tip of the module. The wedge enters the groove, and the module remains in the fixed position (Figure 13c). The part of the module that protrudes beyond the landing adapter is hidden in a specially made pipe or in an element of a weighted drill pipe using an internal rubber centerer.



(**a**)



(**b**)

(**c**)

Figure 13. Assembly diagram of the assembled module in the landing adapter: (**a**) General view of the landing adapter; (**b**) Guide sleeve installed in the landing adapter and fixed with screws; (**c**) Fixation of the module in the guide sleeve.

Since magnetic interference does not affect the sensors of the Smart 4 controller, the body elements can be made of alloy steel, the characteristics of which correspond to industry standards, for example 45XHMA (AISI 4140, or AISI 4145). The landing gear, together with the module, will always be supplied by the service center. If the upper part of the module will be hidden in the weighted drill pipe (it is provided by the drilling contractor), then the final installation will take place on the drilling rig. If the upper part of the module is to be hidden in a special nozzle, then the device will be completely assembled at the production base of the service center. To obtain the recorded information, it will be enough to unscrew the upper fishing neck of the module when lifting the drill string, connect one end of the cable with a special connector to the contact group, and connect the other end of the cable to the laptop via the USB port. The described strategy will make it possible to effectively integrate the module with the vibration sensor into the drill string and ensure the reliable collection of data on the dynamic mode of operation of the drilling tool.

In order to expand the scope of application of the proposed device and to use it at different diameters of the wellbore, the housing part will be manufactured in diameters that correspond to the standard sizes of the weighted drill pipes and other elements of the BHA; namely, 241.1 mm, 228.6 mm, 203.2 mm, 171.4 mm and 127 mm. This will make it possible to measure vibrations when drilling with bits with a diameter of 444.5 mm (393.5 mm), 311.15 mm (295.3 mm), 215.9 mm, and 152.4 mm (165.1 mm), which covers all available diameters of wells in the deposits of the Dnipro–Donetsk Basin.

3. Results and Analysis

3.1. Industrial Approval of the Proposed Device for Registering Vibrations—Trip No.1

The Smart 4 controller ("Innova Power Solutions", Canada) with a lithium thionyl chloride power supply battery was installed in a compact module (Figure 11b) and mounted in the body parts at the production base of the service center. Such a device for assessing vibration and shock loads was installed in the lower part of the drill string.

Consider the history of the first trip. The process of construction of an inclined well was underway. After the completion of the next procedure of lowering and lifting operations to a depth of 2210 m, the drilling tool was planted, and the drilling process was resumed. A PDC Ulterra SPL616 (Ulterra Corporate, Calgary, Canada) drill bit was used during the voyage, and drilling took place in rocks of the Middle Carboniferous Bashkir stage. The following BHA was used: 12 ¼ Bit (0.37 m) + 8 Drilling Motor with a 12-sleeve stab and 1.5° bend (8.95 m) + 12 String Stabilizer (1.79 m) + 8 Pony Collar (1.84 m) + 8 UBHO sub (1.05 m) + 8 ¼ NMDC with MWD inside (7.04 m) + 8 ¼ NMDC (8.24 m) + Crossover Sub (0.71 m) + 8 Drill Collar (45.52 m) + Crossover Sub (0.76 m) + 8 Jar (8.69 m) + Crossover Sub (0.75 m) + 8 Drill Collar (27.91 m) + Crossover Sub (1.07 m) + 5 HWDP (27.56 m) + 6 5/8 Friction Reduction Tool (6.24 m) +5 HWDP (28.08 m) + Drill Pipe (to surface).

Starting from a depth of 3200 m, the stabilization section of the directional well was drilled. Initially, the well was deepened in the normal mode without any signs of complications. During drilling at the interval of 3387–3435 m, there was an uncontrolled drop in the zenith angle from 22.5 to 19.8 degrees, although slides were constantly made to set the zenith angle in the direction L10°–R10° (i.e., the deflector was directed toward the zenith angle). After this event, it was decided to lift the drilling tool to inspect the BHA. During the inspection of the bottom of the drill string assembly elements, the stabilizer was found to be loosened, the axial backlash in the BHA elements had increased from 0.5 mm to 30 mm, and the radial backlash was up to 5 mm (Figure 14).

In order to carry out a detailed study of the origin and causes of the detected damage, information was read from the memory of the pitting vibration recording device (the reading was carried out in the field). The diagram of all parameters of the measured oscillations and shocks is presented in Figure 15. Of course, the absolute value of acceleration is measured in the SI system in m/s^2. However, on the accelerogram, the unit of measurement is the acceleration of free fall ($1m/s^2 \approx 0.102$ g).

Below, we detail the complex accelerogram and consider each component registered by the vibration sensor separately. Shocks during drilling are instantaneous transfers of energy from one body to another, which are caused by the impact of the bit, BHA, or drill string against the walls or downhole. Figure 16a shows the change of lateral shocks depending on time, including two directions: the x direction and the y direction (here, the x- and y-axes are the main central axes of the cross-section of the drill string). Figure 16b shows the change in axial shocks (in the direction along the *z*-axis) as a function of time. It should be noted that the severity of consequences of a shock depends on three parameters: the magnitude of the shock, the duration or length of time of the shock, and the frequency or number of shocks.

(**a**) (**b**)

Figure 14. Revision of the BHA after detection of signs of complications: (**a**) A PDM with an unscrewed body stabilizer; (**b**) The output shaft protrusion from the PDM housing exceeds the allowable value by three times (the cause was the occurrence of axial backlash due to the destruction of thrust-bearing separators).

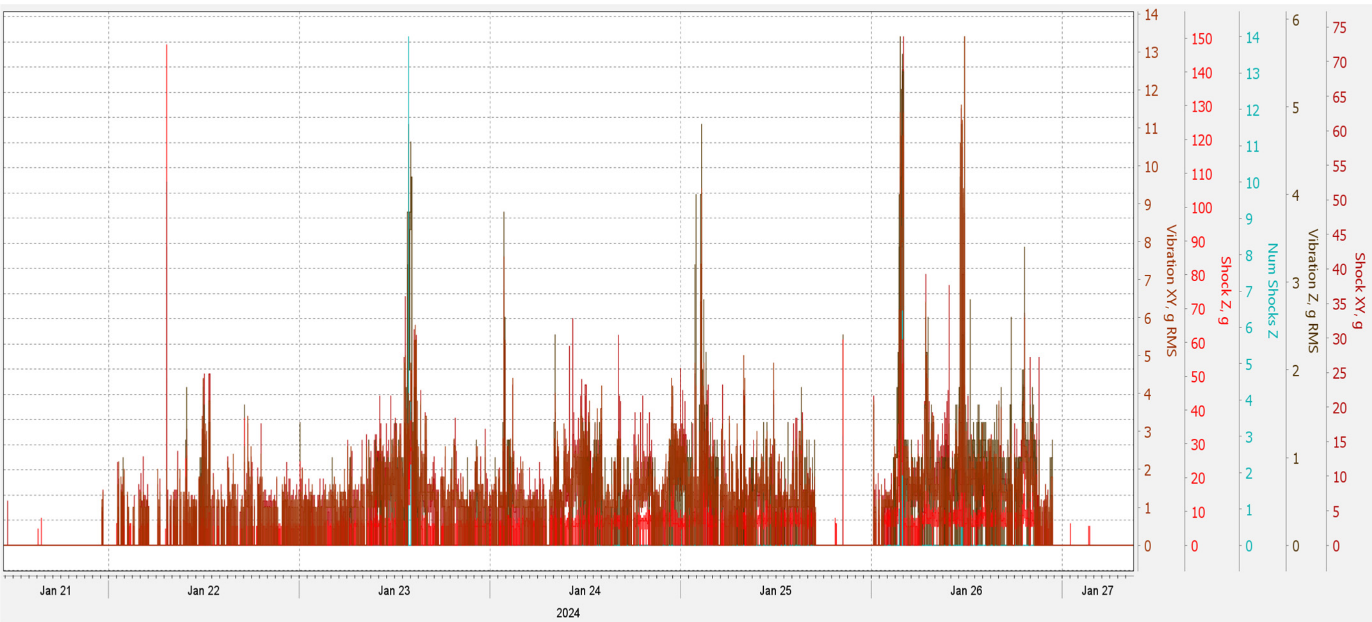
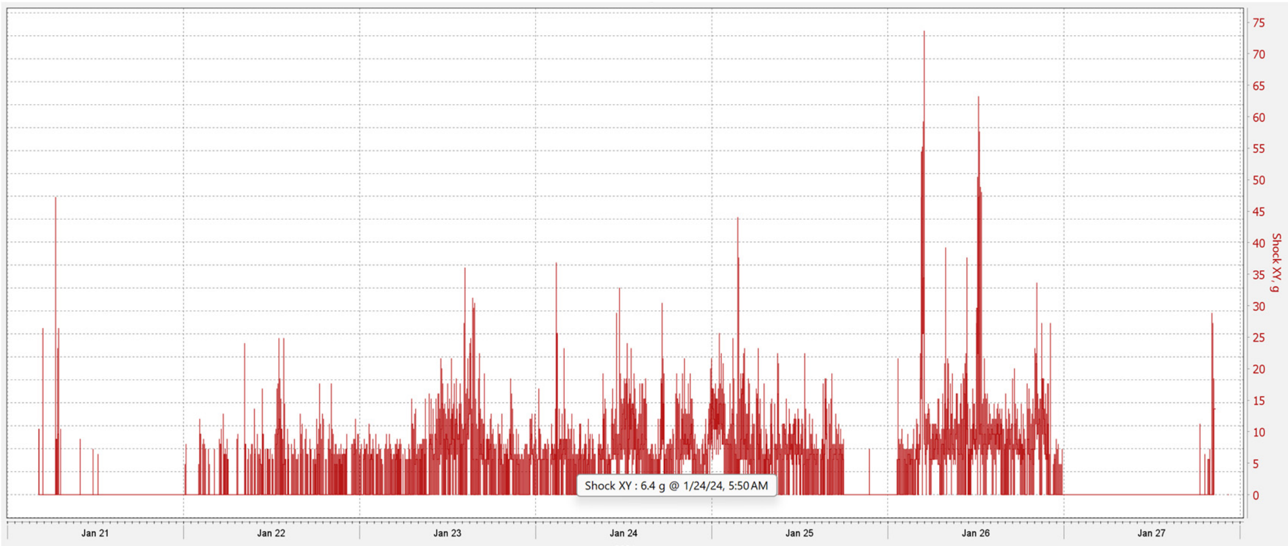
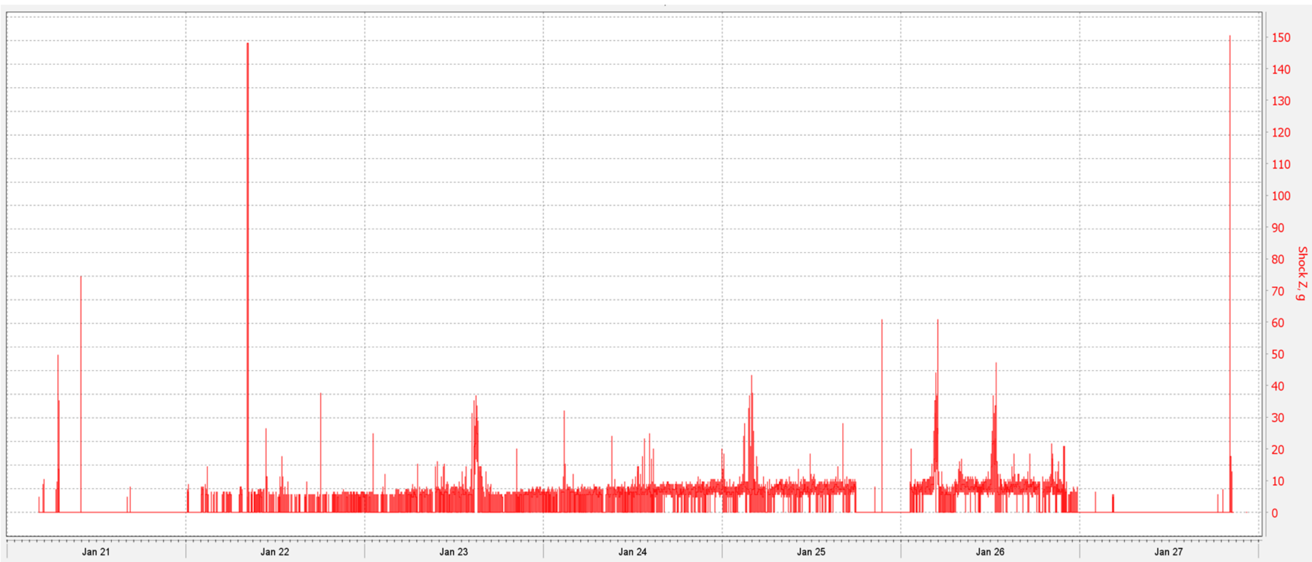


Figure 15. Complex accelerogram read in the field after raising the drilling tool.



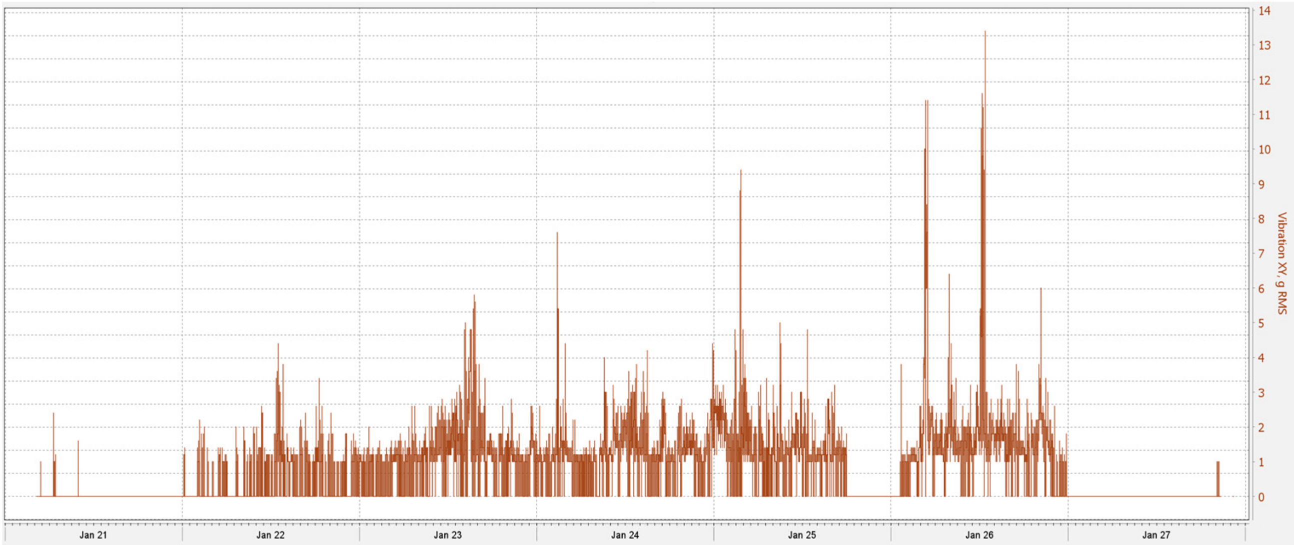
(**a**)



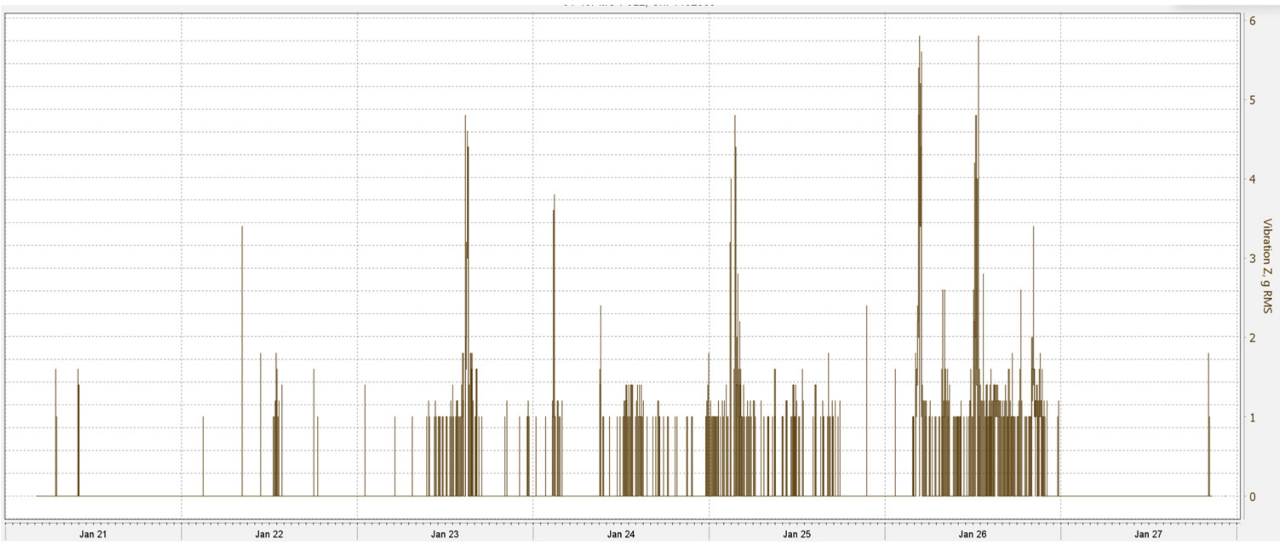
(**b**)

Figure 16. Registration of shocks in three mutually perpendicular directions during the first trip: (**a**) Change in the shocks in lateral directions; (**b**) Changes in the shocks in the axial direction.

For effective assessment of the dynamic regime of the drill string, vibration measurements (Figure 17) are carried out in the RMS (root mean square) system, which means the measurement of the root mean square value of the amplitude of the vibration signal. In the context of drilling tool vibration measurement, RMS indicates the average energy of the vibration signal as perceived by the mechanical system. This allows one to estimate the level of the vibration amplitude, taking into account both the maximum and minimum values of the signal while providing a convenient way to compare vibration signals. In the vibration diagram (Figure 17a), the RMS values of accelerations in the lateral direction (in the direction of the x- and y-axes) are determined on the basis of data that are monitored for ten seconds from the moment of registration of the previous value. The diagram of vibrations in the axial direction (in the direction of the *z*-axis) shown in Figure 17b is the root mean square value of accelerations in units of g determined from data recorded within ten seconds of the moment of fixation of the previous value in the diagram.



(**a**)



(**b**)

Figure 17. Registration of vibrations in three mutually perpendicular directions during the first trip: (**a**) Vibrations in the lateral directions; (**b**) Vibrations in the axial direction.

Figure 18 shows the dependence of "Num Shocks Z" on time. It should be noted here that the measurement takes place in the "CPS Mach (AMx)" mode. Let us reveal each component of the methodology of this measurement: CPS is an abbreviation of "cycles per second", which, in our case, means the number of repetitions of shocks per second; mach (AMx) means "maximum amplitude", which indicates the largest magnitude of shocks detected during measurement. Thus, the dependence in Figure 18 displays the number of shocks in the axial direction, which is measured by the "CPS mach (AMx)" method, and the vibration sensor registers shocks during drilling with an accuracy in relation to the number of oscillations per second, taking into account the maximum amplitude of the magnitude of these oscillations. For example (see Figure 18), a dangerous event was registered on January 23, in which 14 shocks of maximum amplitude in the axial direction occurred within one second.

Figure 18. The number of amplitude shocks in the axial direction during one second (registered during the first trip).

The proposed system is also able to record the value of the number of revolutions of the drilling tool on the wellbore and to register torsional vibrations and evaluate the stick–slip phenomenon. Figure 19 clearly shows the peak values of the acceleration of the drill string during constant rotation of the upper drive system of the drilling rig. It is interesting that at the beginning of the trip, a negative value of the rotation frequency was recorded, that is, the drilling tool periodically moved in the opposite direction in the area of the hole. Analyzing the chronology and timing of the events, we can draw an unambiguous conclusion that the unscrewing of the casing stabilizer of the gas turbine engine took place on the first day of operation of the drilling motor in the well (that is, during the drilling of the interval of 2210–3200 m). Further drilling was accompanied by a significant level of transverse vibrations, which destroyed the thrust-bearing separators. At the end of the flight, an increase in the amplitude and value of axial vibrations and shocks was noted. First of all, this was caused by excessive backlash on the output shaft of the PDM, which was formed after the bearings were damaged. It also explains the unsatisfactory intensity of recruitment and the drop in the zenith angle, which was the reason for the lifting of the drilling tool.

First of all, the occurrence of vibrations is influenced by the rock-destructive tool, namely its type, design and aggressiveness. Also, the diameter of the well and placement of support-centering elements have a significant influence. That is, vibrations are primarily generated by those elements of the drill string that are in direct contact with the hole and the walls of the well. Increasing the depth of the well generally results in greater vibrations due to the longer drill string. A higher rotation speed can cause stronger vibrations (although there are exceptions). Excessive axial load can cause unstable behavior of the drill string and increase vibrations. High flushing fluid pressures and flow rates can affect vibrations. Rock properties, layering, and the presence of defects and inclusions in the rock, etc., have an effect on vibrations.

Accordingly, changing the parameters to reduce vibrations usually means reducing the rotation speed, optimizing the axial load, adjusting the flow rate and pressure of the flushing fluid, supplementing the BHA, using dampers, drilling shock absorbers and stabilizers, and choosing the optimal profile of the drill string.

However, effective control of drill string vibrations requires a comprehensive approach that combines the simultaneous analysis of a number of drilling parameters.

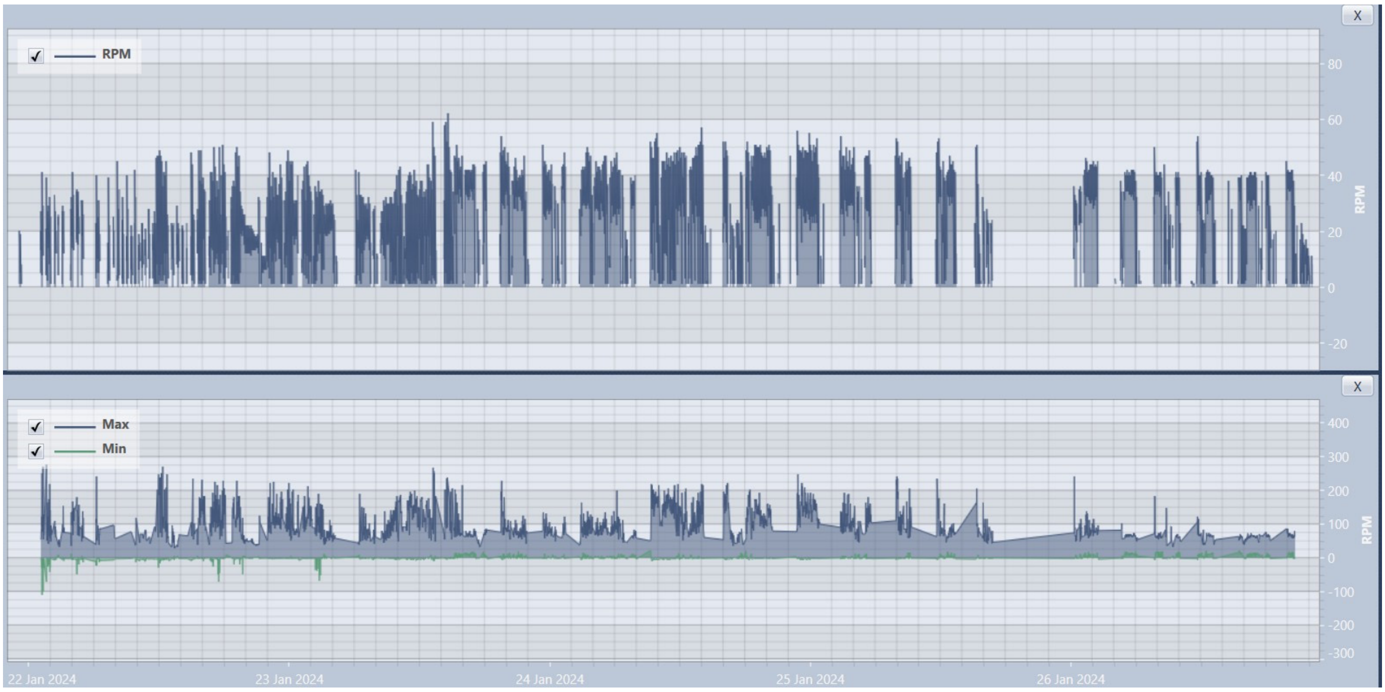


Figure 19. Registration of torsional vibrations in the lower part of the drill string.

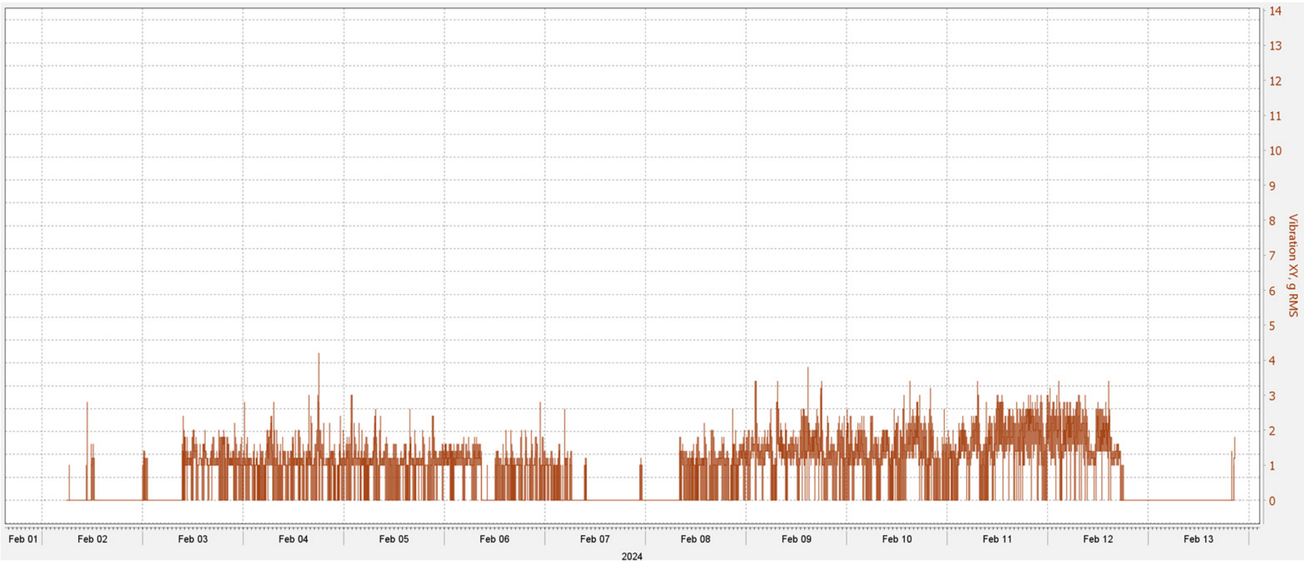
3.2. Changing the Drilling Mode—Trip No. 2

In the previous paragraph, we demonstrated the main capabilities of the controller for recording vibrations at the lower part of the drill string. In the case under consideration, there was a complication of the drilling process, so technological and structural corrections will be made in the next voyage. In general, even in the case of a problem-free trip, the recorded data should be compared with the regulations and recommendations for the safety and efficiency of drilling. If significant deviations from the standards are found, this may require correction of the drilling process or the installation of additional equipment, such as, for example, the drill shock absorber.

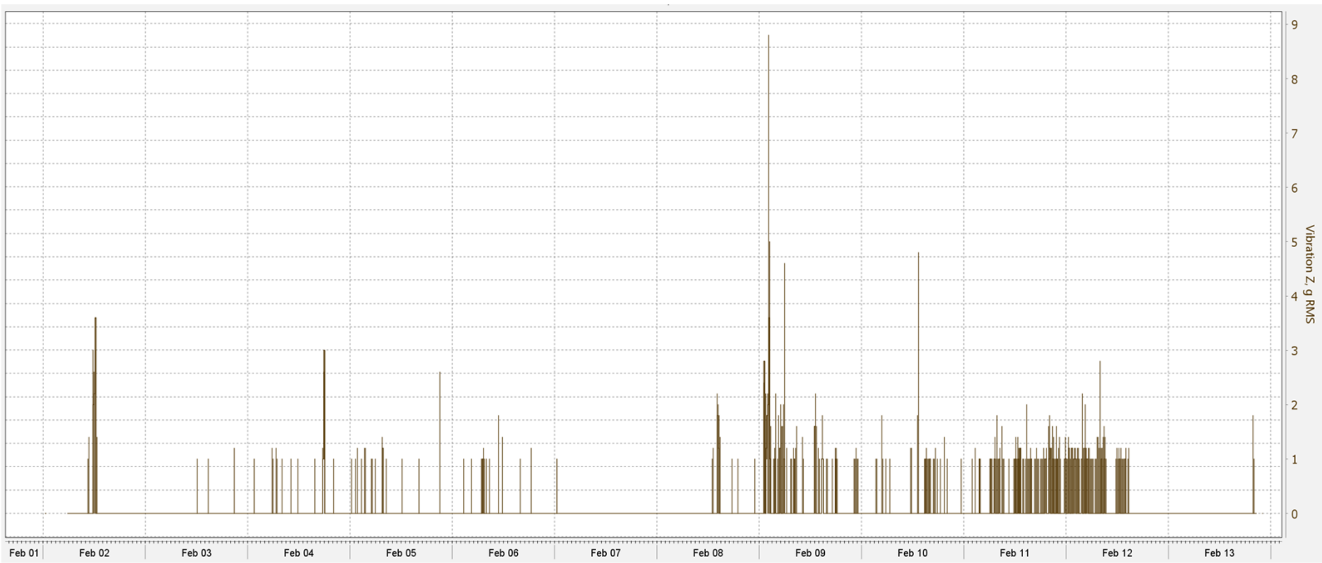
Therefore, after conducting a detailed analysis of the nature and causes of damage to the drilling equipment, the customer was offered the option of carrying out clear monitoring of vibrations in real time using a high-cost telemetry system for a prompt response in the case of dangerous values of vibration loads being registered. In order to prevent the occurrence of drilling complications, it was decided to use the technique of changing the drilling modes; namely, adjusting the rotation frequency of the drill string and varying the axial load. To continue the drilling of the stabilization section of the curvature parameters, the following BHA was assembled in the same well: 12 ¼ Bit (0.37 m) + 8 Drilling motor with a 12-sleeve stabilizer and 1.5° bend (9.06 m) + 11 ¾ String Stabilizer (1.78 m) + 8 Pony Collar (1.84 m) + 8 UBHO (1.05 m) + 8 NMDC with MWD inside (7.04 m) + 8 NMDC (8.24 m) + Crossover sub (0.71 m) + 8 Drill Collar (45.52 m) + Crossover sub (0.76 m) + 8 Drilling Jar (8.69 m) + Crossover Sub (0.75 m) + 8 Drill Collar (27.91 m) + Crossover Sub (1.07 m) + 5 HWDP (28.08 m) + 6 5/8 Friction Reduction Tool (6.37 m) + 5 HWDP (27.34 m) + Drill Pipe (to surface).

Drilling took place in the Bashkir layer, while a PDC Ulterra CF616 bit (Ulterra Corporate, Calgary, Canada) was used. After reaching a depth of 3549 m, inclined directional drilling was started. During the deepening of the well, constant slides were made to maintain its trajectory; between the slides, the drilling process took place in a combined way. Timely changes in drilling modes had a positive effect and made it possible to achieve the desired final result. When the well bore reached the depth of 4066 m, they started raising the drill string for the purpose of core selection. No damage was detected during the inspection of the drilling tool and the hydraulic cylinder (the axial play on the hydraulic cylinder was 1 mm). After lifting the drill string, data were extracted from the memory of the telemetry system and from the Smart 4 controller.

To assess vibrations during the second trip, we chose to measure vibrations in the RMS mode (Figure 20)—this is the determination of the root mean square value of the amplitude of the vibration signal during a certain time interval. Measurement in this mode provides a comprehensive picture of the average level of energy transmitted through vibrations during a certain period of time. This can be useful for assessing the overall impact of vibrations on the drill tool or for comparing vibration levels before and after vibration reduction measures are applied.



(**a**)



(**b**)

Figure 20. Registration of vibrations in three mutually perpendicular directions during the second trip: (**a**) Vibrations in the lateral directions; (**b**) Vibrations in the axial direction.

Comparing the diagrams shown in Figures 17 and 20, it can be concluded that reducing the intensity of vibrations makes it possible to increase the duration of the flight and to keep the out-of-hole equipment intact.

To assess the sensitivity of the proposed Smart 4 controller, a comparison of the data registered with the controller was made with the information obtained from the telemetry system. We graphically compared the absolute values of the vibration accelerations, which were registered without the use of additional mathematical algorithms (Figure 21). Lateral shocks measured in g units during the first trip were taken into consideration (this choice was made because during this flight, most of the events registered in the transverse plane). In the diagram (Figure 21), the LShk parameters are obtained from the Smart 4 controller (marked in orange), and the Shock XY data is obtained using the telemetry system (marked in blue).

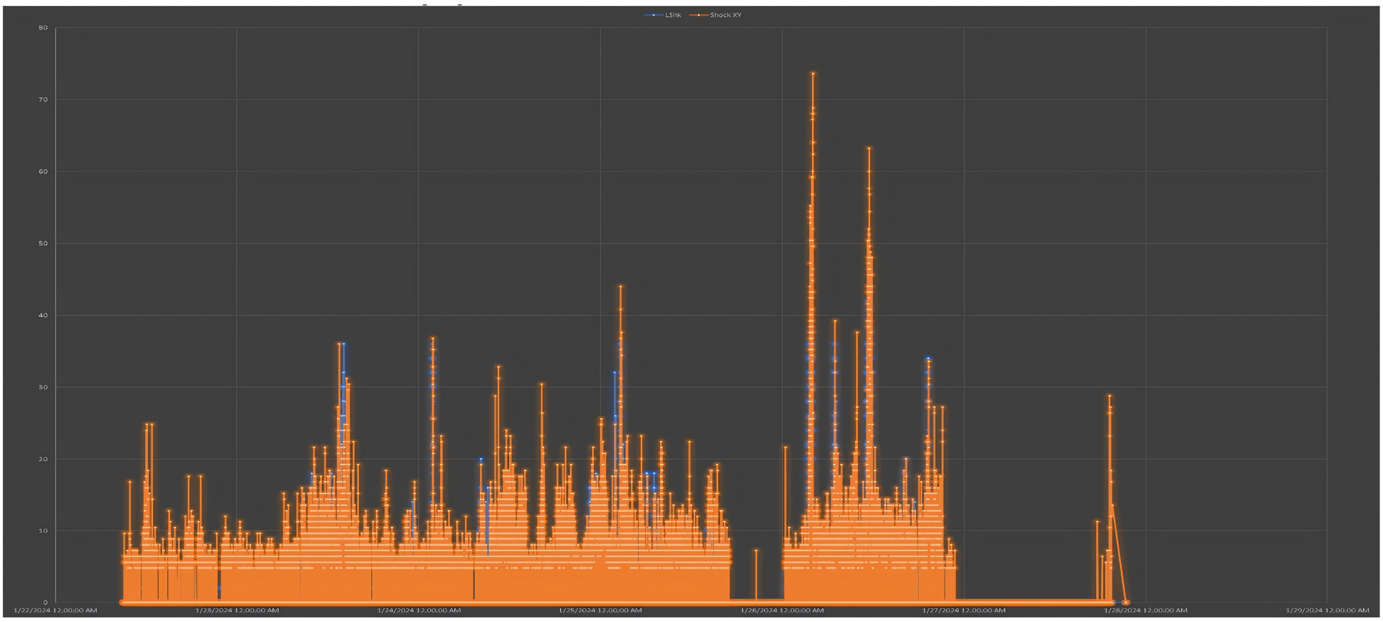


Figure 21. Comparison of the value of shocks in the lateral directions registered during the first trip using different devices: data from the Smart 4 controller are marked in orange; data from the telemetry system are marked in blue.

Graphical visualization shows a good convergence of data obtained by the different measuring devices. It should be understood that this is a pilot study, which first involved checking the design of a module for installing a vibration sensor in the wellbore area and checking the suitability of using a low-cost Smart 4 controller for recording the vibrations of the bottom of the drill string. In the future, it is important to compare the accelerogram data with other drilling parameters, such as the drilling speed, well pressure, well depth, gamma logging, and profilometry results. This will make it possible to better understand the reasons for the increase in vibrations of the tool and, based on the interpretation of accelerograms, to draw conclusions about the influence of vibrations on the drilling process, the efficiency of the drilling equipment, and the safety and quality of the drilling operations. If high-intensity vibrations are detected, it is important to develop measures to reduce them; in particular, to install drilling shock absorbers or other vibration protection devices, to adjust the operating mode of drilling equipment, and to supplement the BHA.

The use of live measurements of drill string vibrations can be useful for improving and refining existing analytical and numerical models of the dynamic processes that occur during the drilling of deep oil and gas wells [71–73]. Comparing the results of field measurements with the predictions of analytical and numerical models makes it possible to assess the accuracy of the models and to make the necessary corrections to improve their compliance in real conditions [74–76]. At the same time, field measurements of vibrations can be used to identify unknown model parameters using the inverse problem method or the system identification method, which will increase the reliability of modeling. Comparison of the simulation results with field measurements makes it possible to check the adequacy of the accepted assumptions and hypotheses laid down in the basis of the models. In addition, the analysis of natural vibration data can reveal new regularities and phenomena that are not taken into account in existing models [77,78]. This can be an impetus for the development of more advanced analytical and numerical models of the dynamic mode of drilling. Thus, the comprehensive use of on-site vibration measurements of the drill string provides an opportunity to increase the adequacy of analytical and numerical models of the dynamic behavior of the drilling tool.

4. Conclusions

Drill string vibration during the oil and gas deep-well construction process is one of the reasons for the high cost of drilling, and its harmful effect reduces the efficiency of drilling and can lead to complications or emergencies. The study carried out a detailed analysis of real case reports of the destructive impact of vibrations that occurred during drilling operations in the fields of the Dnipro–Donetsk Basin. Among the subjective reasons that led to an increase in the intensity of vibrations of the drilling tool, the following are highlighted: the use of aggressively designed drill bits, the use of forced drilling modes, errors in the assembly of the BHA, and ignoring the need to use anti-vibration devices. The main objective reasons for the increase in vibrations during drilling were rock stratification and the phenomenon of contact interaction of the drilling tool with the wall and the hole.

1. In this study, the search for an inexpensive method of recording downhole vibrations and shocks was initiated in order to adjust the dynamic mode of operation of the drill string.
2. To measure the vibrations of the drill string, it is proposed to use the Smart 4 controller, which is equipped with a three-axis accelerometer and a gyroscope, paired with a lithium thionyl chloride battery.
3. A compact module is designed for the reliable placement of the controller in the lower part of the drill string.
4. Industrial testing of the proposed device for measuring vibrations during drilling of an inclined well was carried out, and the registered data were verified using a high-cost telemetry system.

The feature of the proposed controller is its low power consumption and sufficient memory volume, which allows for uninterrupted recording of pothole data over 1000 h of operation, while the accuracy of the data recording is not inferior to much more expensive analogs. The developed module is easily assembled and disassembled, and with its help, the controller is placed in the center of gravity of the cross-section of the drill string, and the design of the module allows for quick unloading of the registered data in field conditions.

The implementation of the proposed method will allow operators to assess the impact of vibrations and shocks when drilling deep wells and to compare the recorded downhole data with critical events that occurred during drilling. At the same time, service departments engaged in the rental, operation, and repair of drilling equipment will be able to obtain an evidence base for resolving warranty disputes. The next stage of research will be devoted to the development of a methodology for conducting two-way accelerogram assessments with the aim of providing recommendations for adjusting the drilling regimes or for the additional completion of the BSC.

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References

1. Li, Y.; Wang, J.; Shan, Y.; Wang, C.; Hu, Y. Measurement and Analysis of Downhole Drill String Vibration Signal. *Appl. Sci.* **2021**, *11*, 11484. [CrossRef]
2. Riane, R.; Doghmane, M.Z.; Kidouche, M.; Djezzar, S. Observer-Based H∞ Controller Design for High Frequency Stick-Slip Vibrations Mitigation in Drill-String of Rotary Drilling Systems. *Vibration* **2022**, *5*, 264–289. [CrossRef]
3. Sharma, A.; Abid, K.; Srivastava, S.; Velasquez, A.; Teodoriu, C. A review of torsional vibration mitigation techniques using active control and machine learning strategies. *Petroleum* **2023**. [CrossRef]
4. Shlyun, N.V.; Gulyayev, V.I. Buckling of a drill-string in two-sectional bore-holes. *Int. J. Mech. Sci.* **2020**, *172*, 105427. [CrossRef]
5. Bembenek, M.; Grydzhuk, Y.; Gajdzik, B.; Ropyak, L.; Pashechko, M.; Slabyi, O.; Al-Tanakchi, A.; Pryhorovska, T. An Analytical–Numerical Model for Determining "Drill String–Wellbore" Frictional Interaction Forces. *Energies* **2024**, *17*, 301. [CrossRef]
6. Liu, W.; Yang, F.; Zhu, X.; Chen, X. Stick-slip vibration behaviors of BHA and its control method in highly-deviated wells. *Alex. Eng. J.* **2022**, *61*, 9757–9767. [CrossRef]
7. Kamgue Lenwoue, A.R.; Deng, J.; Feng, Y.; Li, H.; Oloruntoba, A.; Songwe Selabi, N.B.; Marembo, M.; Sun, Y. Numerical Investigation of the Influence of the Drill String Vibration Cyclic Loads on the Development of the Wellbore Natural Fracture. *Energies* **2021**, *14*, 2015. [CrossRef]
8. Shatskyi, I.; Makoviichuk, M.; Vaskovkyi, M. Transversal Straining of Pressurized Pipeline Caused by Vibration of Damaged Foundation. *Springer Proc. Math. Stat.* **2024**, *453*, 501–508. [CrossRef]
9. Kulke, V.; Thunich, P.; Schiefer, F.; Ostermeyer, G.-P. A Method for the Design and Optimization of Nonlinear Tuned Damping Concepts to Mitigate Self-Excited Drill String Vibrations Using Multiple Scales Lindstedt-Poincaré. *Appl. Sci.* **2021**, *11*, 1559. [CrossRef]
10. Velichkovich, A.S.; Dalyak, T.M. Assessment of stressed state and performance characteristics of jacketed spring with a cut for drill shock absorber. *Chem. Pet. Eng.* **2015**, *51*, 188–193. [CrossRef]
11. Kessai, I.; Benammar, S.; Doghmane, M.Z.; Tee, K.F. Drill Bit Deformations in Rotary Drilling Systems under Large-Amplitude Stick-Slip Vibrations. *Appl. Sci.* **2020**, *10*, 6523. [CrossRef]
12. Ejike, C.; Obuobi, I.F.; Avinu, S.; Abid, K.; Teodoriu, C. Investigation and Analysis of Influential Parameters in Bottomhole Stick–Slip Calculation during Vertical Drilling Operations. *Energies* **2024**, *17*, 622. [CrossRef]
13. Cheng, Z.; Zhang, L.; Hao, Z.; Ding, X.; Liu, Z.; Li, T. A New Bottom-Hole Assembly Design Method to Maintain Verticality and Reduce Lateral Vibration. *Processes* **2024**, *12*, 95. [CrossRef]
14. Chudyk, I.; Sudakova, D.; Dreus, A.; Pavlychenko, A.; Sudakov, A. Determination of the thermal state of a block gravel filter during its transportation along the borehole. *Min. Miner. Depos.* **2023**, *17*, 75–82. [CrossRef]
15. Liu, X.; Zhang, H.; Niu, Y.; Lin, G.; Liu, W.; Li, Y. Experiment on the influence of downhole drill string absorption & hydraulic supercharging device on bottom hole WOB fluctuation. *Energy Rep.* **2023**, *9*, 2372–2378. [CrossRef]
16. Velichkovich, A.S.; Popadyuk, I.I.; Shopa, V.M. Experimental study of shell flexible component for drilling vibration damping devices. *Chem. Petrol. Eng.* **2011**, *46*, 518–524. [CrossRef]
17. Riane, R.; Doghmane, M.Z.; Kidouche, M.; Tee, K.F.; Djezzar, S. Stick-Slip Vibration Suppression in Drill String Using Observer-Based LQG Controller. *Sensors* **2022**, *22*, 5979. [CrossRef]
18. Svitlytskyi, V.; Iagodovskyi, S.; Bilenko, N. Effect of vibration dampers on the dynamic state of a drill string. *Technol. Audit Prod. Reserves* **2023**, *5*, 32–36. [CrossRef]
19. Landar, S.; Velychkovych, A.; Mykhailiuk, V. Numerical and analytical models of the mechanism of torque and axial load transmission in a shock absorber for drilling oil, gas and geothermal wells. *Eng. Solid Mech.* **2024**, *12*, 207–220. [CrossRef]
20. Velichkovich, A.S. Design features of shell springs for drilling dampers. *Chem. Petrol. Eng.* **2007**, *43*, 458–461. [CrossRef]
21. Xu, Y.; Zhang, H.; Guan, Z. Dynamic Characteristics of Downhole Bit Load and Analysis of Conversion Efficiency of Drill String Vibration Energy. *Energies* **2021**, *14*, 229. [CrossRef]
22. Aarsnes, U.J.F.; van de Wouw, N. Effect of shock subs on self-excited vibrations in drilling systems. *J. Petrol. Sci. Eng.* **2019**, *181*, 106217. [CrossRef]
23. Velichkovich, A.; Velichkovich, S. Vibration-impact damper for controlling the dynamic drillstring conditions. *Chem. Petrol. Eng.* **2001**, *37*, 213–215. [CrossRef]
24. Dutkiewicz, M.; Velychkovych, A.; Shatskyi, I.; Shopa, V. Efficient Model of the Interaction of Elastomeric Filler with an Open Shell and a Chrome-Plated Shaft in a Dry Friction Damper. *Materials* **2022**, *15*, 4671. [CrossRef] [PubMed]
25. Shats'kyi, I.P.; Shopa, V.M.; Velychkovych, A.S. Development of full-strength elastic element section with open shell. *Strength Mater.* **2021**, *53*, 277–282. [CrossRef]
26. Saleh, M.K.A.; Nejatpour, M.; Yagci Acar, H.; Lazoglu, I. A new magnetorheological damper for chatter stability of boring tools. *J. Mater. Process. Technol.* **2021**, *289*, 116931. [CrossRef]
27. Machado, M.R.; Dutkiewicz, M.; Colherinhas, G.B. Metamaterial-based vibration control for offshore wind turbines operating under multiple hazard excitation forces. *Renew. Energy* **2024**, *223*, 120056. [CrossRef]

28. Ma, B.; Dong, S. Coupling Simulation of Longitudinal Vibration of Rod String and Multi-Phase Pipe Flow in Wellbore and Research on Downhole Energy Efficiency. *Energies* **2023**, *16*, 4988. [CrossRef]
29. Velichkovich, A.S. Shock Absorber for Oil-Well Sucker-Rod Pumping Unit. *Chem. Petrol. Eng.* **2005**, *41*, 544–546. [CrossRef]
30. Chudyk, I.I.; Dudych, I.F.; Sudakova, D.A.; Voloshyn, Y.D.; Bogoslavets, V.V. Influence of drilling mud pulsations on well cleanout efficiency. *Nauk. Visnyk Natsionalnoho Hirnychoho Universytetu* **2023**, *5*, 48–53. [CrossRef]
31. Panevnik, D.A.; Velichkovich, A.S. Assessment of the stressed state of the casing of the above-bit hydroelevator. *Neftyanoe Khozyaystvo Oil Ind.* **2017**, *1*, 70–73.
32. Prysyazhnyuk, P.; Molenda, M.; Romanyshyn, T.; Ropyak, L.; Romanyshyn, L.; Vytvytskyi, V. Development of a hardbanding material for drill pipes based on high-manganese steel reinforced with complex carbides. *Acta Montan. Slovaca* **2022**, *27*, 685–696.
33. Prysyazhnyuk, P.; Ivanov, O.; Matvienkiv, O.; Marynenko, S.; Korol, O.; Koval, I. Impact and abrasion wear resistance of the hardfacings based on high-manganese steel reinforced with multicomponent carbides of Ti-Nb-Mo-V-C system. *Procedia Struct. Integr.* **2022**, *36*, 130–136. [CrossRef]
34. Ropyak, L.; Shihab, T.; Velychkovych, A.; Bilinskyi, V.; Malinin, V.; Romaniv, M. Optimization of Plasma Electrolytic Oxidation Technological Parameters of Deformed Aluminum Alloy D16T in Flowing Electrolyte. *Ceramics* **2023**, *6*, 146–167. [CrossRef]
35. Shatskyi, I.; Makoviichuk, M.; Ropyak, L.; Velychkovych, A. Analytical Model of Deformation of a Functionally Graded Ceramic Coating under Local Load. *Ceramics* **2023**, *6*, 1879–1893. [CrossRef]
36. Onysko, O.; Kopei, V.; Barz, C.; Kusyi, Y.; Baskutis, S.; Bembenek, M.; Dašić, P.; Panchuk, V. Analytical Model of Tapered Thread Made by Turning from Different Machinability Workpieces. *Machines* **2024**, *12*, 313. [CrossRef]
37. Pryhorovska, T.O.; Ropyak, L. Machining Error Influnce on Stress State of Conical Thread Joint Details. In Proceedings of the 8th International Conference on Advanced Optoelectronics and Lasers (CAOL 2019), Sozopol, Bulgaria, 6–8 September 2019; pp. 493–497. [CrossRef]
38. Kopei, V.; Onysko, O.; Kusyi, Y.; Vriukalo, V.; Lukan, T. Investigation of the Influence of tapered Thread Pitch Deviation on the Drill-String Tool-Joint Fatigue Life. In *Lecture Notes in Networks and Systems, New Technologies, Development and Application V. NT 2022*; Karabegović, I., Kovačević, A., Mandžuka, S., Eds.; Springer: Cham, Switzerland, 2023; Volume 472, pp. 144–154. [CrossRef]
39. Hossain, N.; Rimon, I.H.; Mimona, M.A.; Mobarak, H.; Ghosh, J.; Islam, A.; Al Mahmud, Z. Prospects and challenges of sensor materials: A comprehensive review. *e-Prime* **2024**, *7*, 100496. [CrossRef]
40. Chen, Q.; Li, J. Study on the Mechanism and Suppression of Harmonic Vibration of AMB-Rotor System. *Vibration* **2024**, *7*, 83–97. [CrossRef]
41. Bembenek, M.; Makoviichuk, M.; Shatskyi, I.; Ropyak, L.; Pritula, I.; Gryn, L.; Belyakovskyi, V. Optical and Mechanical Properties of Layered Infrared Interference Filters. *Sensors* **2022**, *22*, 8105. [CrossRef]
42. Wright, R.F.; Lu, P.; Devkota, J.; Lu, F.; Ziomek-Moroz, M.; Ohodnicki, P.R., Jr. Corrosion Sensors for Structural Health Monitoring of Oil and Natural Gas Infrastructure: A Review. *Sensors* **2019**, *19*, 3964. [CrossRef]
43. Shatskyi, I.P.; Makoviichuk, M.V.; Shcherbii, A.B. Influence of Flexible Coating on the Limit Equilibrium of a Spherical Shell with Meridional Crack. *Mater. Sci.* **2020**, *55*, 484–491. [CrossRef]
44. Dutkiewicz, M.; Velychkovych, A.; Andrusyak, A.; Petryk, I.; Kychma, A. Analytical Model of Interaction of an Oil Pipeline with a Support of an Overpass Built in a Mountainous Area. *Energies* **2023**, *16*, 4464. [CrossRef]
45. Tsao, Y.-C.; Vu, T.-L. Determining an optimal sensor system for smart buildings with uncertain energy supply and demand. *J. Build. Eng.* **2023**, *71*, 106532. [CrossRef]
46. Liang, H.; Chen, H.; Zou, J.; Bai, J. Technical research on realizing remote intelligent diagnosis of petroleum drilling loss circulation under smart city strategy. *Future Gener. Comput. Syst.* **2021**, *125*, 91–99. [CrossRef]
47. Shan, Y.; Xue, Q.; Wang, J.; Li, Y.; Wang, C. Analysis of the Influence of Downhole Drill String Vibration on Wellbore Stability. *Machines* **2023**, *11*, 762. [CrossRef]
48. Li, Y.; Xue, Q.; Wang, J.; Wang, C.; Shan, Y. Pattern recognition of stick-slip vibration in combined signals of DrillString vibration. *Measurement* **2022**, *204*, 112034. [CrossRef]
49. Saadat, S.M.; Prakasan, H.; Poothia, T.; Pandey, G. A comprehensive study on vibration control and evaluation of drill string during drilling operation. *AIP Conf. Proc.* **2023**, *2855*, 040009. [CrossRef]
50. Dong, G.; Chen, P. A Review of the Evaluation, Control, and Application Technologies for Drill String Vibrations and Shocks in Oil and Gas Well. *Shock Vib.* **2016**, *2016*, 7418635. [CrossRef]
51. Maitra, E.K.; Al Dushaishi, M.F.; Sugiura, J.; Jones, S. Experimental Visualization of Downhole Drilling Vibration Using Industrial Drilling Dynamic Recorder. In Proceedings of the International Petroleum Technology Conference 2024, Dhahran, Saudi Arabia, February 2024. Paper Number: IPTC-23494-MS. [CrossRef]
52. Liu, J.; Huang, H.; Zhou, Q.; Wu, C. Self-Powered Downhole Drilling Tools Vibration Sensor Based on Triboelectric Nanogenerator. *IEEE Sens. J.* **2022**, *22*, 2250–2258. [CrossRef]
53. Mustapha, S.; Lu, Y.; Ng, C.-T.; Malinowski, P. Sensor Networks for Structures Health Monitoring: Placement, Implementations, and Challenges—A Review. *Vibration* **2021**, *4*, 551–585. [CrossRef]
54. Tian, J.; Wei, L.; Yang, L. Research and experimental analysis of drill string dynamics characteristics and stick-slip reduction mechanism. *J. Mech. Sci. Technol.* **2020**, *34*, 977–986. [CrossRef]
55. Qu, J.; Xue, Q.; Wang, J.; Sun, J.; Lu, J.; Zhang, H.; Sun, F.; Xinghua, T. From Design to Experimental Validation of the Fully Mechanical Gravity Tool Face Measurement-While-Drilling System. *SPE J.* **2024**, *29*, 2971–2987. [CrossRef]

56. Hassan, I.U.; Panduru, K.; Walsh, J. An In-Depth Study of Vibration Sensors for Condition Monitoring. *Sensors* **2024**, *24*, 740. [CrossRef] [PubMed]
57. Zhang, J.; Liang, H.; Chen, Z. The technology of intelligent recognition for drilling formation based on neural network with conjugate gradient optimization and remote wireless transmission. *Comput. Commun.* **2020**, *156*, 35–45. [CrossRef]
58. Liu, J.; Pan, G.; Wu, C.; Feng, Y. Research on Hybrid Vibration Sensor for Measuring Downhole Drilling Tool Vibrational Frequencies. *Appl. Sci.* **2024**, *14*, 5014. [CrossRef]
59. Wang, R.; Ren, J.; Ding, W.; Liu, M.; Pan, G.; Wu, C. Research on Vibration Accumulation Self-Powered Downhole Sensor Based on Triboelectric Nanogenerators. *Micromachines* **2024**, *15*, 548. [CrossRef] [PubMed]
60. Liu, Z.; Lei, K.; Song, J.; Li, L.; Li, T. A Designed Calibration Approach for the Measurement-While-Drilling Instrument. *Appl. Sci.* **2023**, *13*, 61. [CrossRef]
61. Wang, H.; Huang, H.; Wu, C.; Liu, J. A Ring-Shaped Curved Deformable Self-Powered Vibration Sensor Applied in Drilling Conditions. *Energies* **2022**, *15*, 8268. [CrossRef]
62. Yu, Y.; Liu, Q.; Han, B.S.; Zhou, W. Application of Convolutional Neural Network to Defect Diagnosis of Drill Bits. *Appl. Sci.* **2022**, *12*, 10799. [CrossRef]
63. Senjoba, L.; Sasaki, J.; Kosugi, Y.; Toriya, H.; Hisada, M.; Kawamura, Y. One-Dimensional Convolutional Neural Network for Drill Bit Failure Detection in Rotary Percussion Drilling. *Mining* **2021**, *1*, 297–314. [CrossRef]
64. Benmir, N.; Akroum, H.; Doghman, M.Z.; Kidouche, V. A Survey Study of Modeling, Analysis, and Control Drill String under Torsional, Axial, and Lateral Vibrations. In Proceedings of the Second International Conference on Energy Transition and Security (ICETS), Adrar, Algeria, 12–14 December 2023; pp. 1–11. [CrossRef]
65. Lyu, F.; Wang, Y.; Mei, Y.; Li, F. A High-Frequency Measurement Method of Downhole Vibration Signal Based on Compressed Sensing Technology and Its Application in Drilling Tool Failure Analysis. *IEEE Access* **2023**, *11*, 129650–129659. [CrossRef]
66. Zhang, L.; Ning, Z.; Peng, H.; Mu, Z.; Sun, C. Effects of Vibration on the Electrical Performance of Lithium-Ion Cells Based on Mathematical Statistics. *Appl. Sci.* **2017**, *7*, 802. [CrossRef]
67. Innova Power Solutions. Smart-4 Technolology. Available online: https://www.innova-power.com/smart-4-technology.html (accessed on 29 March 2024).
68. Hua, X.; Thomas, A. Effect of dynamic loads and vibrations on lithium-ion batteries. Journal of Low Frequency Noise. *Vib. Act. Control* **2021**, *40*, 1927–1934. [CrossRef]
69. Halliburton. Well Construction Suite. *Wellplan-Software.* Available online: https://www.halliburton.com/en/software/decisionspace-365-enterprise/decisionspace-365-well-construction/well-construction-suite/wellplan-software (accessed on 29 March 2024).
70. Deng, K.; Hu, W.; Ge, L.; Hu, Z.; Yang, Q.; Xiao, X. Study of Downhole Lateral Force Measurement Modelling and Devices in Petroleum Exploration. *Energies* **2022**, *15*, 5724. [CrossRef]
71. Liu, W.; Ni, H.; Wang, Y.; Guo, Y.; Gao, Y.; He, P. Dynamic modeling and load transfer prediction of drill-string axial vibration in horizontal well drilling. *Tribol. Int.* **2022**, *177*, 107986. [CrossRef]
72. Shatskii, I.P.; Perepichka, V.V. Shock-wave propagation in an elastic rod with a viscoplastic external resistance. *J. Appl. Mech. Tech. Phys.* **2013**, *54*, 1016–1020. [CrossRef]
73. Hai, W.; He, Y.; Xue, Q. Research on the Influence of Deep-Water Drilling Risers on Drillstring Motion Trajectory and Vibration Characteristics. *Machines* **2024**, *12*, 112. [CrossRef]
74. Moysyshyn, V.M.; Lyskanych, M.V.; Borysevych, L.V.; Vytyaz, O.Y.; Voznyi, I.I. Experimental Estimation of Design and Drilling Regime Option Influence on Drilling Tool Dynamics. *Metallofiz. I Noveishie Tekhnologii* **2021**, *43*, 689–712. [CrossRef]
75. Wang, R.; Liu, X.; Song, G.; Zhou, S. Non-Linear Dynamic Analysis of Drill String System with Fluid-Structure Interaction. *Appl. Sci.* **2021**, *11*, 9047. [CrossRef]
76. Shatskyi, I.; Perepichka, V. Problem of dynamics of an elastic rod with decreasing function of elastic-plastic external resistance. In *Dynamical Systems in Applications, Proceedings of the DSTA 2017, Lodz, Poland, 11–14 December 2017*; Awrejcewicz, J., Ed.; Springer: Cham, Switzerland, 2018; Volume 249, pp. 335–342. [CrossRef]
77. Ichaoui, M.; Schiefer, F.; Ostermeyer, G.-P. A Novel Mesoscopic Drill Bit Model for Deep Drilling Applications. *Modelling* **2023**, *4*, 296–322. [CrossRef]
78. Yan, B.; Tian, J.; Meng, X.; Zhang, Z. Stick–Slip Vibration Characteristics Study of the Drill String Based on PID Controller. *Energies* **2023**, *16*, 7902. [CrossRef]