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RESEARCH NOTE

Designing a High Resistant, High-torque Downhole Drilling Motor

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ABSTRACT

Downhole drilling motors or mud motors are frequently used during the oil and gas well construction, especially for construction of directional and horizontal segments. However, low operation life of the down hole drilling motors and high rate of wear in their working elements may constrain their application due to technical and economical disadvantageousness. In this work, a high-torque modular motor is designed and used. Results of the theoretical and experimental investigations show that the developed down hole motor is characterized by lower torsional vibrations, improved operation stability and restored energy characteristics of the gerotor machine.

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1. INTRODUCTION

Currently there is a wide usage of downhole drilling motors (DHM): from 45 to 50% as a bit drive during construction of oil and gas wells. In the present drilling technology, there are several instability problems associated with DHM operation, such as its shutoffs, low operation life of the working elements (WE) and failure of the drill string (DS) assembly. In particular, motor operation life can last from 90 to 235 hours depending on the size and operating conditions.

DHM failure occurs from 5 to 12 times per year that leads to an extra recovery work in the hole or well abandonment [1]. The main causes of less effective reliability, service durability and working efficiency of DHM can be listed as follows:

- low wear resistance of the working elements [2-4];
- limited temperature durability of stator elastomer;
- deformation of stator covering associated with redistribution of interference in rotor – stator pair and shifting of the rotor in radial direction [5, 6].

Partial solution to provide the higher wear resistance of WE is to use mud lubricants which have higher tribotechnical characteristics. However, lubricants do not completely meet the requirements, which are needed to maintain the drilling mud rheological parameters and to extend the service life of DHM's, as the thermal variations may significantly affect the performance of the lubricants and thus the stability of DHM's. The solution also can be found in changing the design of working elements (their shape and geometrical parameters) to partition the force sections. However, these solutions cannot facilitate the increase of DHM torsional vibrations, its stability factor and service life. Therefore, it is necessary to design and develop: 1) high-torque DHMs without partitioning of gerotor mechanisms; 2) devices providing increased starting characteristics of the volumetric motors and 3) modular motors with higher stability factor and longer service life.

2. METHODOLOGY AND EXPERIMENTS

The diametrical tension change as a function of elastometer and the rotor diameters ratio, is studied considering different wear rate of the working elements (for 30 motors of type D2-195 after being used for 20,

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40, 60, 80, 100 hours). For the new motor the following values are accepted: tension coefficient = 0.10; eccentricity e in range of 4.5 mm; the diameter of the rotor on the teeth top df = 125.54 mm; the diameter of the stator elastomer on the cavity dc = 134.76 mm; diametrical tension δ = 0.47 mm. The following trends can be concluded after running the motor in the well: reduction in the average diameter of the rotor on the teeth top, increase in the diameter of the stator on the cavity and reduction in the average diametric tension. The trends are represented in Figure 1.

Based on the results, it is established that after 100 running hours, the wear of the working elements is 45%, where 33% of which occurs in the first 60-100 working hours of the motor in the well. Meanwhile, the more intensive wear is observed in the rubber of the stator elastomer. The wear of the stator is no more than 0.15 mm, which is stipulated by big difference of the strength properties between the interactive surfaces (rubber and steel) of the working elements. In addition, the stator wear depends on the high hydro-mechanical resistances of the working part's spiral surfaces in the running process related to the raised (to 0.4 mm) diametric tension in rotor-stator pair [7].

The energy characteristics of the motors in the wells is studied in the transient state (from optimum to brake) with constant consumption of the technical fluid Qconst =0.030 m3/sec and maintaining the motor's shaft rotation frequency from 9.3 to 10.4 sec-1 (Figure 2).

It's evident from the figure that with the diametric tension decrease in the working element from 0.47 to 0.25 mm, the pressure of the motor dropped from 6.5 to 3.17 MPa and the torque of the shaft reduced from 7.2 to 2.1 kNm. The reduction of the motor's energy characteristics leads to failure in its further exploitation, as it becomes impossible to keep up the required drilling parameters. To restore output performance of gerotor mechanism, which has worked more than 100 hours in the well, it is required to increase the contact stress in WE to save absolute stability of motor performance. Functional relation of contact stress can be shown as follows:

$$\sigma_H = f\left(\sqrt{PE_{young}}, i, c_0, c_e, \xi, c_T, c_\delta, k\right) \tag{1}$$

where, P – pressure drop in the motor; E_{young}– Young's modulus of WE materials; $i, c_0, c_e, \xi, c_T, c_\delta, k$ – non-dimensional parameters of gerotor mechanism.

With the given motor capacity, it is not possible to change contact stress by adjusting P and E_{young}, because P is specified by the torque and E_{young} does not change significantly.

However, changing the motor eccentricity e leads to the reduction of torsional vibration (smaller value of Fin and larger value of Fh) and increase of indication moment M_{ind} and contact stress σ_H, which finally increase the DHM performance stability [8, 9].

Contact stress (diametric tension) increase and eccentricity reduction (e) of the motor is achieved due to the fact that in DHM (Figure 3), the rotor of georotor mechanism is divided into several modules (3.4 and 5) according to the helix lead.

The DHM includes gerotor mechanism, containing stator (1) with inner helical lobes, rotor (2) with outer helical lobes (the quantity of which is 1 piece less than the number of stator inner lobes, and inner helical lobes of stator are made from viscoelastic material like rubber, cured into the inside surface of the stator).

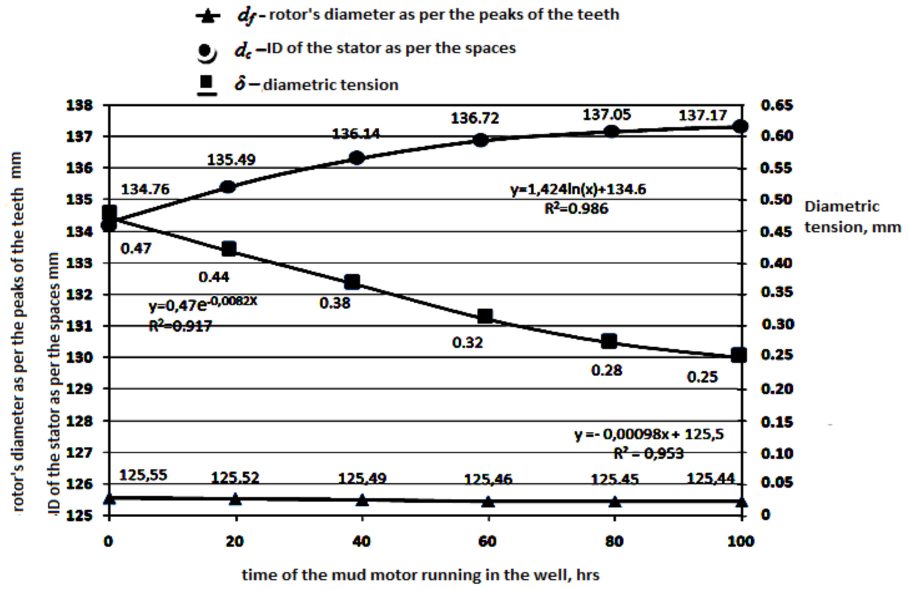


Figure 1. Variations of the downhole motor D2-195 parameters with respect to the motor running time in the well

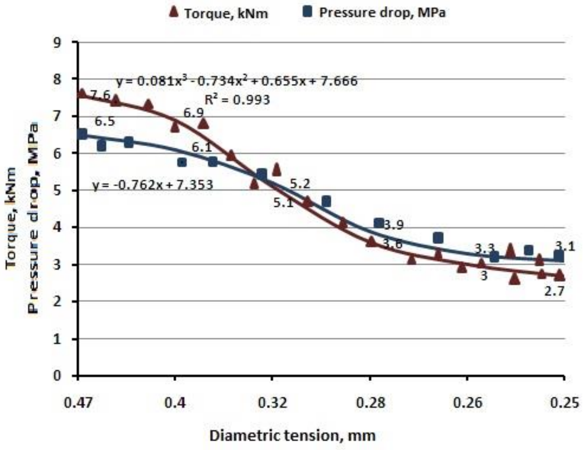


Figure 2. Changes in the energy characteristics of D2-195 as a function of diametric tension (after the motor had been operating in the well from 20 to 100 hours)

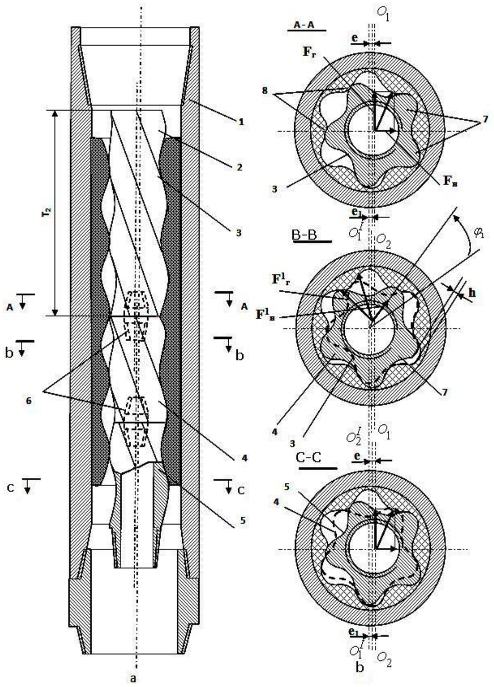


Figure 3. Motor with increased motor capacity: a- gerotor mechanism; b – front sectional view of combined modules

Modules are coaxially combined with the help of threaded connection (6). The axis $O_1^I O_2^I$ of the module (4) is extended with the angle of φ with respect to the static stator and is extended with the angle φ_1 with respect to the axis O_1O_2 of the modules (3) and (5).

Values of the angles φ and φ_1 correspond to the wear limit of the stator elastic material, i.e. the maximum of contact stress during linking of addendums of rotor and stator. The angles can be calculated using the following formulas:

$$\varphi = 360^0\left(\frac{Z_1 - Z_2}{Z_1 \cdot Z_2}\right) \tag{2}$$

$$\varphi_1 = 360^0 \cdot \frac{Z_1}{Z_2} \cdot \left(\frac{Z_1 - Z_2}{Z_1 \cdot Z_2}\right) \tag{3}$$

where, Z1, Z_2 are the number of rotor and stator teeth.

By turning the module (4) with the angle φ_1, its lobes (7) are moved along stator lobe generating line (from stator horn φ_1 = 0 degrees) to the top of the lobe. Depending on the turn angle of module (4), axes O_1O_2 of modules (3) and (5) are displaced as large as h. Displacement value (h) of the axis of the module (4) reduces the eccentricity (e) of the modules (3) and (5) to the e_1. Reduction of eccentricity in the WE of gerotor mechanism with a modular performance, leads to an increase, growth of contact stress on the lobes (8) of modules (3) and (5) (total diametric tension), and also a decrease of inertial force fin, which affect the level of DHM torsional vibrations.

To perform the parametrical analysis of the WE as a function of the modules extension angles, an automated hydraulic tong, which is a part of the test bench “Griffith TORQUEMASTER JUNIOR 1289”, was used. It consists of remote control (1); hydraulic tongs (one - stationary (2), another – able to rotate (3)) (Figure 4).

There is a possibility of horizontal movement of the tong on the setting base (rails) surface (4) which allows performing the assembling of the working parts of the motor.

During the assembly of the motor, especially during connection of the rotor (5) with the stator (6), the contact friction force between the screw surface of the rotor (5) and the screw teeth of the stator rubber elastomer (6) should be defined.

The fixation of the threads (7) and adjustment of the modules (8), (9) turn angle φ1 relative to each other is performed using a movable tool (3) (Figure 5). Control of the modules (8) and (9) turn angle (φ) relative to each other is performed using a protractor and by application of reprint method (Figure 6).

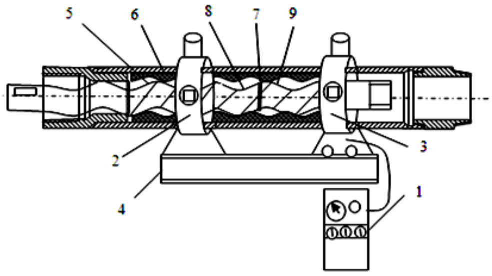


Figure 4. A scheme of the automated hydraulic tong (with possibility to adjust the angle φ of the modules turn)

During the change of modules turn angle (φ), direction of the rotor's screw line is shifted [10].

Initially to define the shift in modules teeth, the surface of modules screw lines (teeth's peaks) are covered with lubrication or painted with a marker. Then, the material is overlaid (with a paper sheet for example) and the changed direction of teeth's peaks screw line (3), (4) and the modules screw line (1), (2) are printed (Figure 6). Then, the shift h of the modules screw line is measured and the value of the angle φ1 is calculated as follows:

$$\varphi_1 = 2\pi h / l \tag{4}$$

where, h – shift of the screw line, mm; l – a perimeter of circle; d_f – OD of the rotor on the teeth top, mm.

3. THE ENERGY CHARACTERISTICS OF THE DOWNHOLE MOTOR WITH THE GEROTOR MECHANISM AND MODULAR DESIGN

The working parts of the modular design motor and its energy characteristics is studied by applying the downhole motor D2-195 (used in the previous experiment) having the wear of the working elements more than 40 %. The testes were carried out with the constant liquid consumption Qconst = 0.030 m3/sec.

In Figure 7, the influence of the modules turn angle on the energy characteristics of the modular design motor is also presented. As soon as the modules turn angle changes from 1 to 30, the diametric tension increases from 0.25 mm to 0.47 mm and the motor's torque from 2.0 to 5.9 kN·m. However, at the module turn angle of more than 40, the diametric tension increases to 0.52 mm, pressure increases in the motor to 4.5 MPa, and rotation frequency drops to 5.0 sec-1 (47 rpm).

The rotation frequencies less than 70 rpm do not fit the requirements for working with the high-torque matrix-performance bits and leads to the reduction of mechanical velocity of well deepening process. The optimum rotation frequency should vary from 70 to 120 rpm.

Therefore, for the tested motor the module turn angle (φ1) should be ranged from 3 to 40, with the rotation frequency from 7.4 to 10.0 sec-1 and torque from 4 to 4.9 kNm.

Figure 5. Adjustment of the modules turn angle φ

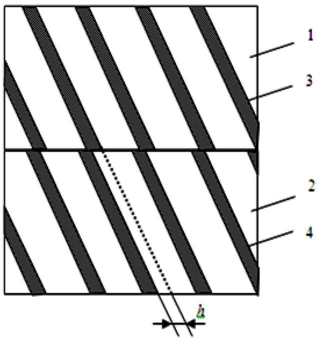


Figure 6. Reprint of the modules screw surface (the developed profile of the screw line)

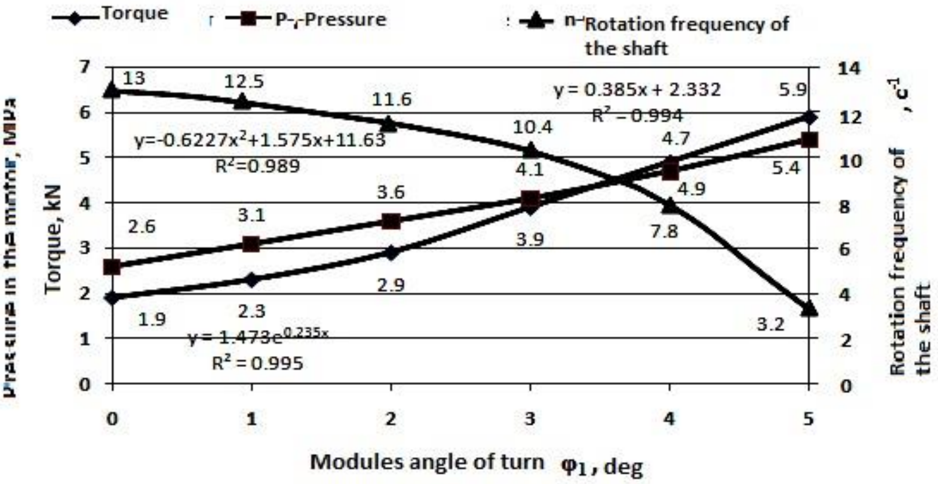


Figure 7. Relation of the shaft torque, pressure and rotation frequency with the modules turn angle (φ1)

These parameters will satisfy the required conditions of drilling operation.

The recommended values of the modules turn angle (φ_1) as a function of diametric tension for D2-195 are presented in the Table 1.

The investigation results showed that the modular performance of the gerotor mechanism allows to restore the energy characteristics of the used (worn to 40 %) motor for 35 – 55 % (torque from 2.2 to 4.9 kNm; frequency from 6,2 to 10.4 sec-1; pressure from 3.3 to 4.3 MPa).

4. THE TRANSVERSE VIBRATIONS LEVELS OF THE DOWNHOLE MOTOR BEFORE UPGRADING AND WITH THE GEROTOR MECHANISM OF THE MODULAR DESIGN

The torsional vibrations of the motor's body was studied with the used and upgraded (the rotor with the modular design) screw motors like D1-195, DGR-178.6.7.57 and DGR-178.7/8.37.

The technical characteristics of the experimental motors operated in the wells from 90 to 120 hours are as follows:

D1-195- eccentricity e 4.2 mm; diameter of the rotor on the teeth top df = 125.40 mm; diameter of the stator elastomer on the cavity dc = 137.25 mm; δ = 0.23 (fluid consumption Qconst = 0.030 m3/sec).

DGR-178.6.7.57 - eccentricity e 8.5 mm; diameter of the rotor on the teeth top df = 122.10 mm; diameter of the stator elastomer on the cavity dc = 135.25 mm; δ = 0.16 (fluid consumption Qconst = 0.032 m3/sec).

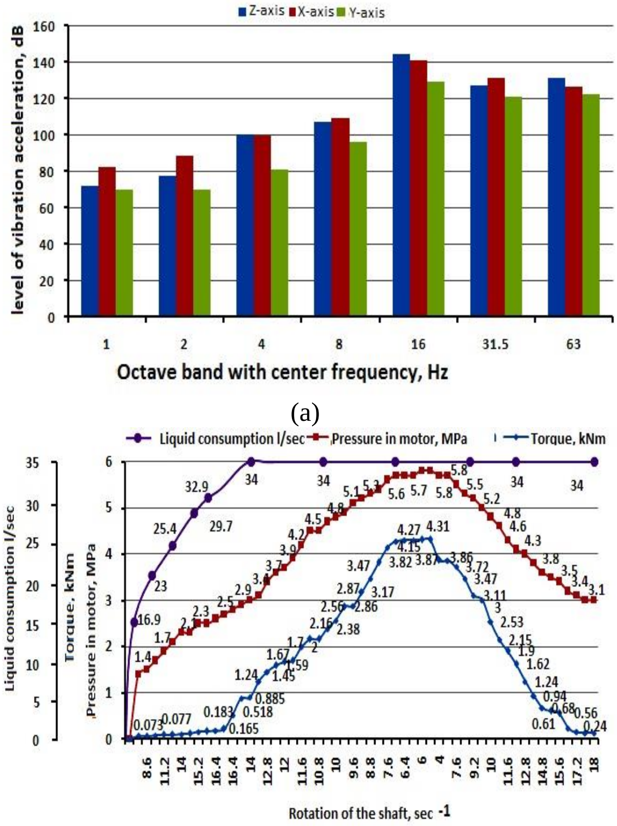
DGR-178.7/8.37 - eccentricity e 6.2 mm; diameter of the rotor on the teeth top df = 122.10 мм; diameter of the stator elastomer on the cavity dc = 135.20 мм; δ = 0.13 (fluid consumption Qconst = 0.034 m3/sec). The modules angle of turn φ1 ranged from 3 to 50.

The results of the research on the vibration level of the motor DGR-178.7/8.37 with simultaneous measurement of its energy characteristics (2 min) before and after upgrading a modular partition of the motor's rotor, are presented in Figures 8-10.

TABLE 1. The recommended values of the modules angle of the turn φ1 depending from the diametric tension for D2-195

№	The diametric tension of the used downhole motor, mm	The modules turn angle φ_1, deg.
1	0,22	3-4,5
2	0,25	3-4
3	0,28	2,5-3,5
4	0,31	2-3
5	0,34	1,5-2,5

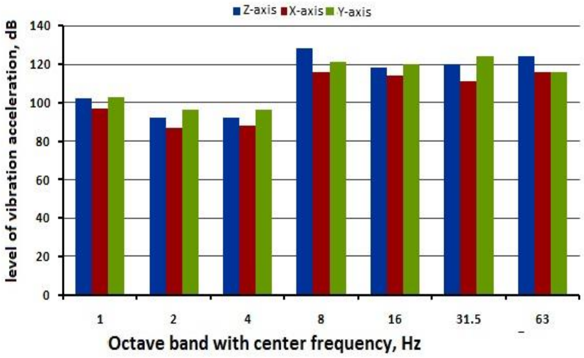
The study of DGR-178.7/8.37 showed that vibration acceleration of the motor (in maximum power efficiency) before upgrading was varying from 140 to 146 dB with frequency 16 Hz (vibration speed was from 0.1 to 0.82 m/sec) (Figure 8a).



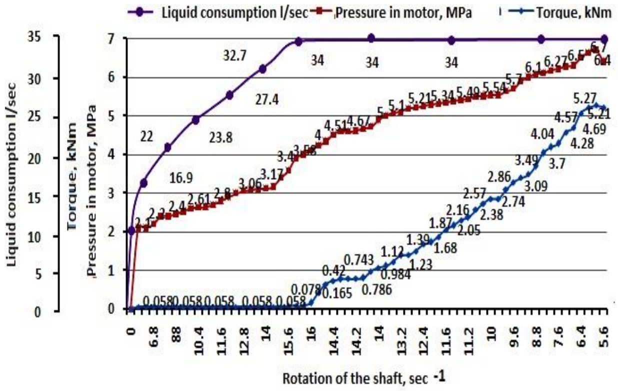
(a)

(b)

Figure 8. Vibration Level (a) and energy characteristics (b) of DGR-178.7/8.37 prior upgrading



(a)



(b)

Figure 9. Vibration level (a) and energy characteristics (b) of DGR-178.7/8.37 after upgrading (modular partition of the rotor with the turn angle φ1 = 40)

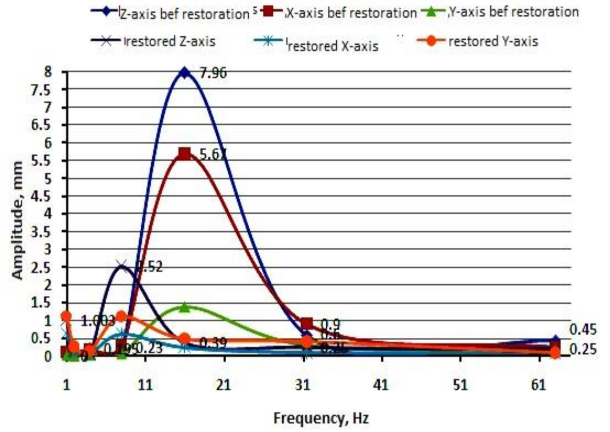


Figure 10. DGR-178.7/8.37 body's beat amplitude before and after upgrading (modular division of the rotor)

After upgrading, the level of vibration acceleration dropped from 121 to 136 dB (vibration speed from 0.01 to 0.02 m/sec) and the maximum value was fixed on the frequency of 8 Hz (Figure 9a). The motor's amplitude (Figure 10) after upgrading reduced from 8.0 to 2.6 mm.

5. CONCLUSION

The study of the designed downhole drilling motors showed that the braking torque before upgrading was no more than 3830 Nm, and with the optimum (recommended for PDC bits no less than 100 rpm) rotation -2000 Nm. After upgrading, the torque raised from 2000 to 3100 Nm and the maximum braking torque from 3800 to 4567 Nm. The liquid consumption during testing was kept 33-34 liters/sec. In average, the energy characteristics of DGR-178.7/8.37 after upgrade increased 18-23 %.

During the investigation of the torsional vibrations in the motor DGR-178.6/7.57 before and after upgrading, the similar measurement of the energy characteristics was conducted as the same for the DGR-178.7/8.37. The braking moment of the motor before upgrade was 3851 Nm, and after that– 5036 Nm with the same shaft's rotation frequency (208 rpm) and fluid consumption (34 liters/sec). In average, the energy characteristics of the motor DGR-178.6/7.57 after upgrade increased 19-21 %.

The analysis of the motors vibration investigation before and after upgrading showed that the vibration has decreased 1.5-2 times. The reduction of the torsional vibrations helped to improve the operation stability of the downhole motor in the maximum efficiency and to restore the energy characteristics of the gerotor machine by 18-25 % in average.

The results of the theoretical and experimental researches can serve as a basis for development of the downhole motor with modular design followed by testing of the motor at the field conditions.

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چکیده

موتورهای حفاری زیرزمینی یا موتورهای گل در اغلب موارد در ساخت و ساز چاه های نفت و گاز، به ویژه برای ساخت بخش های هم جهت و افقی مورد استفاده قرار می گیرند. با این حال، عمر عملکردی پایین موتورهای حفاری کم عمق و نرخ بالای سایش در عناصر کار می تواند به دلیل کمبود فنی و اقتصادی آنها را محدود کند. در این کار، یک موتور مدولار با گشتاور بالا طراحی و استفاده می شود. نتایج تحقیقات نظری و تجربی نشان می دهد که موتور توسعه یافته کم عمق توسط ارتعاشات تسریعی پایین تر، ثبات عملکردی بهبود یافته و ویژگی های انرژی ذخیره شده دستگاه مهر و موم خصوصیت دهی می شود.

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