American Journal of Applied Sciences

Original Research Paper

Development of Small Hydraulic Downhole Motors for Well Drilling Applications

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Article history
Received: 27-05-2016
Revised: 05-10-2016
Accepted: 05-10-2016

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Abstract: Further development of the well drilling technologies becomes possible due to the improvement of rock cutting tools and hydraulic downhole motors. When developing a new hydraulic motor, it is highly important to eliminate rotor vibrations and reduce motor size. There are two main trends in further improvement of hydraulic motors: The upgrade of the downhole screw motors currently in use and the development of new reliable geared turbodrills. Besides, the R&D works are underway to construct a roller vane motor for downhole drilling. The experts of Gubkin Russian State University of Oil and Gas have launched a new R&D programme aiming at developing a hybrid hydraulic system combining the best features of a screw motor and a roller vane motor. The hybrid hydraulic system could be a radical solution to the problem of rotor vibrations in a hydraulic motor. The R&D activities conducted by Gubkin Russian State University of Oil and Gas are intended to create an advanced downhole drilling motor for the cutting tools with high-torque bits rotating at a speed of 240 to 450 rpm. The main area of application of the hybrid hydraulic motor is horizontal drilling of oil and gas fields. Yet, some R&D findings can be used for performing other production tasks, e.g., designing the pumping facilities for oil and gas extraction and pumping.

Keywords: Hydraulic Downhole Motor, Drilling, Well, Oil, Gas

Introduction

Nowadays, mostly directional and horizontal wells are drilled when developing the oil and gas fields. The area of high-torque PDC bit application is constantly expanding. Mainly Downhole Screw Motors (DSM) are used referring to positive displacement hydraulic motors and having higher power performance compared to turbodrills classified as dynamic hydraulic motors (Baldenko and Korotaev, 2012; Baldenko *et al*., 2007; Pittard *et al*., 2015; Rogers and Maurer, 2007; Ranjbar and Sababi, 2012). The analysis of the technical and scientific publications shows that, regardless of their country of origin, DSMs have similar controllability when drilling, while their main problems are short operating time and frequent failures. In this context, the scientific research aiming to design an improved hydraulic motor appears to be of great importance. According to the experts (Baldenko and Korotaev, 2012; Baldenko *et al*., 2007; Ranjbar and Sababi, 2012) the causes for the DSM short lifetime include the abrasive wear of the cutting tools, limited temperature range for the stator elastomer, deformation of the stator elastic coating resulting in the radial displacement of the rotor under the influence of deforming forces, as well as lateral vibrations of the motor rotor and housing. The rotor's axis is displaced from the stator by the eccentricity equal to the half of the tooth depth. When the rotor performs a planetary motion, the torsional vibrations of the motor occur resulting in the reduced DSM capacity caused by the rotor design, as well as the behavior of the drilling mud pulses. The centrifugal force generated by the rotating rotor directs the rotor towards the stator coating. With the high frequency of translational rotation, the centrifugal force causes intensive lateral vibrations adversely affecting the life of the power section.

The cutting tool wear changes the geometry, diametral clearance and eccentricity of DSM negatively impacting its power characteristics. For high power performance, the gerotor mechanism shall have fixed gear clearance values. Gear clearance is a key parameter for the gerotor mechanism. Inadequate clearance could cause drilling mud leakages, as well as reduce the efficiency, rotary torque and wear margin of the gerotor mechanism. Too large a clearance would cause either the binding of the teeth, or their early destruction due to the excessive deformation and high friction between the stator and the rotor teeth. To ensure an optimum gear clearance for the maximum life span of the gerotor mechanism, the diametral dimensions, teeth profile and circular and axial pitch of the stator and the rotor teeth shall be in line with the designed configuration parameters. The gear clearance is also affected by the noncylindricity of the rotor and the curvature of the stator channel. Given the above information, we can conclude that the rotor and the stator are critical high precision components having no equivalents in general and special engineering (Baldenko and Korotaev, 2012; Baldenko *et al*., 2007).

The drilling equipment market is witnessing a competition between DSMs and turbodrills. PDC bits with no support elements represent a new generation of diamond drilling tools requiring a medium rotation speed of 240 to 450 rpm. Normally, it does not fit into the range of speeds for the normal operation of serial turbodrills. To be able to operate in such modes, turbodrills are fitted out with reduction gears. Thus, the development of reliable reduction gears for turbodrills is of major importance for the improvement of the turbodrilling efficiency.

Modern high performance high-torque PDC bits can be efficiently used only with highly reliable, durable and powerful hydraulic downhole drives. At present, much attention is paid to the following innovation projects (Baldenko and Korotaev, 2012) aiming at the improvement of the DSM cutting tools: (1) increased length of the cutting tools could significantly reduce the wear rate and the bearing pressure in gear, as well as prevent the early destruction of the rubber teeth due to excessive deformation and rubber heating; longer lifetime due to increased length of the cutting tools can also be explained by their longer hours in service before the gear clearances reach 0.5 mm and more; (2) reduced rotor weight would minimise the impact of the inertial lateral loads on the motor assembly; with the high frequency of translational rotation and significant weight of the rotor travelling along the orbit, strong centrifugal forces occur generating intensive lateral vibrations adversely affecting the lifetime of the stator and other motor components; (3) the use of stators with a uniform thickness of the elastic coating (profiled or armored stators) could make DSM a classical positive displacement machine whose rotary torque does not virtually depend on the mud consumption and the rotation speed-on the rotary torque. Some experts believe that it is possible to make stators entirely of metal rather than of metal and elastomer, if a motor design provides for a clearance between the rotor and the stator (Pafitis and Koval, 2001; Johnson and Rtrihafka, 1998; Leroy and Flamme, 1995; Kochnev *et al*., 1993).

The analysis of the scientific and technical publications on hydraulic machines shows that, apart from DSMs and turbodrills, the R&D activities encompass roller vane motors (Harris and Susman, 1998; McPhate *et al*., 2002; Teale and Marshall, 2007) and downhole twin-screw motors (Gynz-Rekowski von, 1999). In addition, the scientists are exploring the possibilities for developing a hybrid hydraulic machine combining the best features of a screw motor and a roller vane motor (Sazonov and Rybanov, 2015; Sazonov *et al*., 2012). The development of hybrid hydraulic machines has a long history (Rolkerr, 1919; Engberg, 1950; Paesons, 1974; Iida *et al*., 1989; Hirotsugu *et al*., 1992; Atsushi, 2000). Yet, further improvement of hybrid hydraulic systems is possible only with the use of new structural materials and low-wear diamond bearings (Judd, 2015). Hybrid hydraulic solutions could be deployed for designing a next-generation hydraulic downhole motor for drilling oil and gas wells.

The analysis of scientific literature has shown that to improve the efficiency of drilling oil and gas wells, using the PDC bits, new hydraulic downhole motors are required that can operate reliably at a rotor rotation frequency ranging from 240 to 450 revolutions per minute. The existing screw downhole motors are unable to effectively operate at a rotor speed due to radial vibrations of the rotor in such a motor. The radial rotor vibrations are determined by the design features of the screw downhole motor, where the rotor center of mass moves along the orbital path, causing vibration. Thus, it can be concluded that the problem of rotor vibration in the screw downhole motors remains unsolved. In this regard, it is highly relevant to carry out research works on creation of a new hydraulic motor lacking the rotor vibration. The essence of research problem is to provide a new hydraulic motor operating on different principles, which would eliminate vibration at a rotor rotation frequency in the range from 240 to 450 rpm.

Concept Headings

As technology develops, hard alloys and other hard materials become more commonly used for the manufacture of hydraulic machines. However, the problem of processing of helicoid and other geometrically complicated surfaces made of hard materials is yet to be solved. In this context, it is extremely important to construct a new easy to manufacture positive displacement hydraulic motor with a simple design (Sazonov and Rybanov, 2015; Sazonov *et al*., 2012).

The experts of Gubkin Russian State University of Oil and Gas have launched a new R&D program aiming to develop a hybrid hydraulic system combining the best features of a screw motor and a roller vane motor (Sazonov and Rybanov, 2015; Sazonov *et al*., 2012). A hybrid hydraulic motor is a reversible machine that can operate in both the pumping and motoring modes. Combined theoretical and experimental research of pumping machinery made it possible to find new ways for further development of such hydraulic systems.

The research procedure is interdisciplinary in nature. Given that the rotor vibration problem is connected with the operation principle of a screw downhole motor, a decision was made to look for new operating principles for creating a new hydraulic motor. It was decided to go beyond the classical theory developed for screw downhole motors. It was decided to carry out the pilot study at the junction of the two technical areas, in the area between the screw and vane hydraulic machines.

Alongside with that, the research is carried out in two directions, as the new hydraulic machine is a comprehensive one and can be used both as a pump and a hydraulic motor (Sazonov *et al*., 2012). The first line of research is related to the creation of new pumps for oil production (Sazonov and Rybanov, 2015). The second line of research concerns the creation of new hydraulic motors for drilling oil and gas wells.

This article discusses research results referring only to the second line of work.

Results

The laboratories of Gubkin Russian State University of Oil and Gas carry out persistent research and development to create new technology or equipment, including hydraulic motors for well drilling applications. The hydraulic motor (Sazonov *et al*., 2012) shown in Fig. 1 and 2 comprises housing 1 with inlet pipe 2 and outlet pipe 3, tube 4 with spiral channels and helical rotor 5 eccentrically positioned in tube 4 with a potential for the radial displacement of tube 4 from rotor 5. Tube 4 is concentrically positioned in bore 6 of housing 1 forming groove seals 7 in a clearance between tube 4 and housing 1. Rotor 5 is positioned in close proximity to the surface of bore 6 of housing 1 forming groove seal 8 in a clearance between the outer surface of rotor 5 and the surface of bore 6 in housing 1 with a potential for the formation inside housing 1 of consecutive spiral chambers 9 separated by groove seals 7 and 8. Rotor 5 is fitted out with locking devices 10 used to prevent the displacement of tube 4 from rotor 5. Tube 4 consists of consecutive separate sections 11 and 12 with a potential for the angular displacement of some sections relative to the other. The sections in tube 4 are positioned along the spiral line forming the stepped structure resembling the spiral staircase. Rotor 5 is supported by bearings 18 ensuring that rotor 5 is eccentrically positioned in tube 4 and inside bore 6 of housing 1. Tube 4 is concentrically positioned inside bore 6 of housing 1. In Fig. 1, tube 4 consists of separate bushings (vanes) 11 and 12 each of which, for instance, covers a sector of 120 degrees.

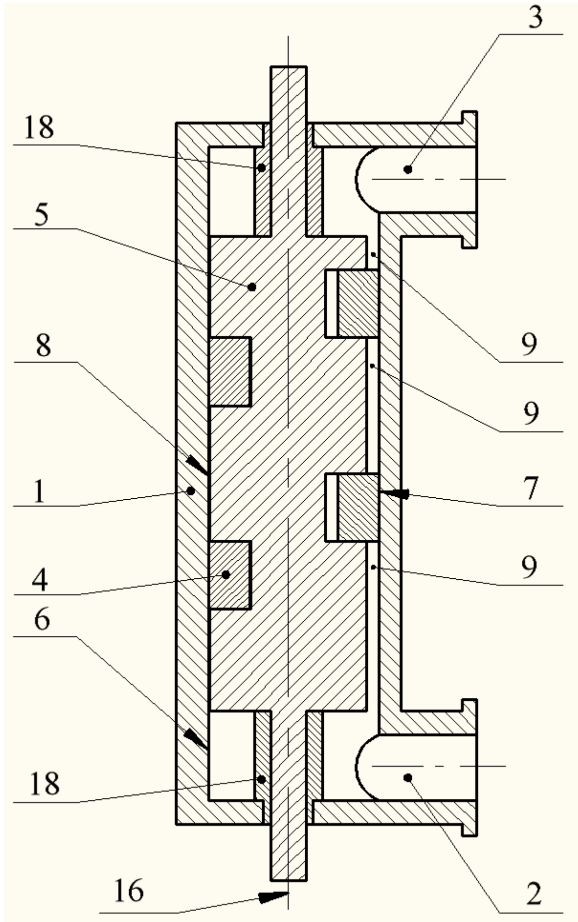

Fig. 1. Downhole Screw Motor (Sazonov *et al*., 2012) according to RF Patent 116188

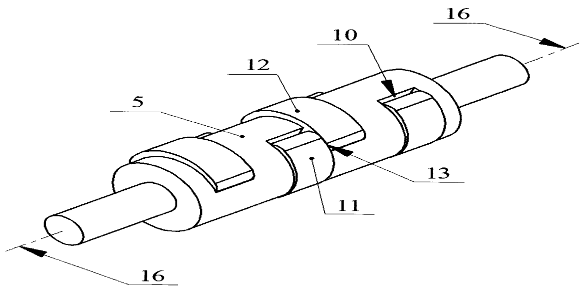

Fig. 2. Screw Motor Rotor (Sazonov *et al*., 2012) according to RF Patent 116188

The description of the screw motor operation in the motoring mode can be seen below. Drilling mud is introduced under excessive pressure into inlet pipe 2. Groove seals 7, 8 and 13 prevent high capacity losses and ensure gradual pressure changes in consecutive chambers 9. The pressure reaches its maximum value equal to that at the motor inlet in spiral chamber 9 connected to inlet pipe 2. The minimum pressure levels equal to those at the motor outlet are reached in spiral chamber 9 connected to outlet pipe 3. Forces induced by the pressure drop between adjacent chambers 9 generate a rotary torque actuating tube 4 and rotor 5, as rotor 5 is eccentrically positioned in tube 4 with a potential for the radial displacement of tube 4 from rotor 5. The above forces act on rotor 5 and tube 4 causing their rotational motion. The hydraulic energy is converted into the mechanical energy. The power generated by rotating rotor 5 actuates the bits of the cutting tool.

Three-dimensional modelling makes it possible to consider more closely the application of the angular bushings (Sazonov and Rybanov, 2015). In 2016 the design work and laboratory tests of hydraulic machines with angular inserts shown in Fig. 3 and 4 were continued.

In the first half of 2016 several variants of hydraulic machines differing in design were tested. In one embodiment, each operating chamber in the hydraulic machine had three angular inserts. In another embodiment, each operating chamber in the hydraulic machine had six angular inserts. The hydraulic machine body of the laboratory-scale plant was made of a transparent material, which allowed perform photo and video shooting directly in the process of hydraulic machine operation.

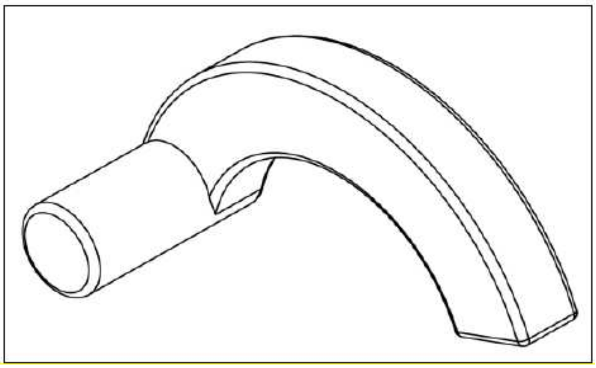

Fig. 3. 3D Model of the angular bushing for the hydraulic motor

Fig. 4. 3D Model of the rotor with angular bushings for the hydraulic motor

Discussion

A new small-sized powerful hybrid motor (Sazonov and Rybanov, 2015; Sazonov *et al*., 2012) has been developed combining the best features of a single screw motor and a roller vane motor. The technology applied could eliminate the drawbacks of the already existing hydraulic motors. The present-day screw motors for downhole drilling have the rotor travelling along the orbit and generating undesirable lateral vibrations of the motor and the bit negatively affecting the drilling performance. The new solution (Sazonov and Rybanov, 2015; Sazonov *et al*., 2012) enables the development of a borehole screw motor with no radial vibrations of the rotor and the bit during the drilling operations. It would solve the problem of rotor vibrations that is the most common problem of all positive displacement machines.

The theoretical background and calculation methodology required for the development of a new hydraulic machine have been prepared. The new technology (Sazonov and Rybanov, 2015; Sazonov *et al*., 2012) could also solve the problem of the motor operability at high temperatures, as the updated motor contains no elastomeric components.

The manufacturability and repairability of the hydraulic motor have been significantly improved, with the motor chambers having simpler and easier to process cylindrical and flat surfaces (Sazonov and Rybanov, 2015; Sazonov *et al*., 2012). The technically complicated spiral components have been excluded from the motor technical drawings, since processing of hard spiral surfaces is a costly operation. Flat and cylindrical surfaces are easier to process, which made it possible to launch the production of diamond bearings (Judd, 2015). Diamond with unique properties. When designing a new machine, developers often seek out the simplest design that eventually turns out to be the cheapest and the most reliable one.

The development of new hydraulic motors for well drilling applications has been theoretically substantiated (Sazonov *et al*., 2012). The motor suffers no vibration from the rotating rotor. The stator has no elastomeric components. It ensures increased specific loads, reduced length and longer lifetime of the motor due to the use of low-wear super-hard materials for the rotor and the stator. The works on the hydraulic motor are at their initial stage. The first functional tests have been completed recently. They were carried out in a laboratory environment on the special micromodels shown in Fig. 5 and 6.

The bench tests on micromodels and prototypes of the new hydraulic motor have been completed (Sazonov and Rybanov, 2015; Sazonov *et al*., 2012). The micromodels were tested at a shaft speed of 200 to 3,000 rpm. At such speeds, no radial vibrations of the shaft were recorded. The functional tests were performed using fluids with varying viscosities (from 1 to 1,500 cSt).

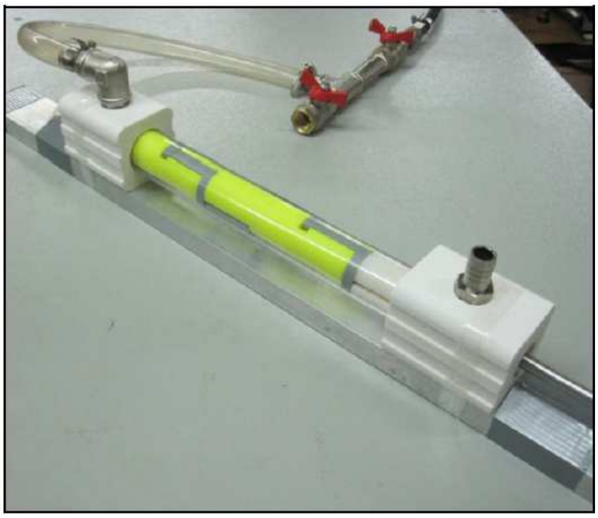

Fig. 5. New hydraulic motor micromodel (Option)

Fig. 6. One rotor section of the multi-section hydraulic motor micromodel (Option)

It has been experimentally proven that the rotor and the stator of the hydraulic motor can be made entirely of metal rather than of metal and elastomer. However, for special purposes, elastomers with various elastic properties can be used, as elasticity has no impact on the operation of the sealing devices of the hydraulic machine.

There are two main approaches to the development of downhole screw motors. Some experts believe that it is possible to make the stator entirely of metal, if a motor design stipulates a clearance between the rotor and the stator (Pafitis and Koval, 2001; Johnson and Rtrihafka, 1998; Leroy and Flamme, 1995; Kochnev *et al*., 1993). Others argue that solely metalelastomer power section can ensure reliable and efficient operation of a downhole drilling motor. Some developers automatically apply their knowledge of downhole screw motors to all types of hydraulic machines, including those yet to be created. Taking into account the apparent conflict of interest, it should be stated that the new hydraulic motor (Sazonov and Rybanov, 2015; Sazonov *et al*., 2012) can be made either entirely of metal, or of metal and elastomer. It has become possible due to the new design of the hydraulic motor providing for a wear compensation system for groove sealings.

At this stage (Sazonov and Rybanov, 2015; Sazonov *et al*., 2012), we can draw a preliminary conclusion on the good prospects for the new hydraulic downhole motor. The new technology could underlie the experimental model of the hydraulic motor for well drilling applications.

Laboratory tests conducted in 2016 showed that to form operating chambers in the new hydraulic machine it is possible to use different configurations. Moreover, the embodiments having operating chambers with three and six angular inserts were successfully tested. These studies have confirmed a possible variety of options to create hydraulic machines of a new type.

Conclusion

The analysis of the scientific and technical publications reveals several trends in the R&D activities aiming at developing a hydraulic downhole motor for the cutting tools with high-torque bits rotating at a speed of 240 to 450 rpm. The downhole screw motors and geared turbodrills currently in use in the industry are being improved. A roller vane motor for downhole drilling is being developed. Beyond that, the experts of Gubkin Russian State University of Oil and Gas have launched a new R&D program aimed at developing a hybrid hydraulic system combining the best features of a screw motor and a roller vane motor. A hybrid hydraulic system could be a radical solution to the problem of rotor vibrations in a hydraulic motor. It also creates additional opportunities for the efficient use of new low-wear structural materials, since the operating chambers of the motor have simple and easy to process flat and cylindrical surfaces. The new motor can be made either entirely of metal, or metal and elastomer. It has become possible due to the new design of the hydraulic motor providing for a wear compensation system for groove sealings.

The results of the R&D works (2015-2016) have revealed good prospects for the new hydraulic motor intended for well drilling purposes. The cylindrical surface of the rotor has the vanes positioned along the spiral line. The rotor has the vane-shaped grooves ensuring radial movement of the vanes in the rotor grooves. The cylindrical rotor is positioned in the cylindrical housing with the eccentricity equal to the half of the difference between the housing and rotor diameters. Such motor can operate in both the motoring and pumping modes. The pump mode tests have proven the ability of the hydraulic motor to pump low to high viscosity media. The interim findings enable us to continue our research aiming at developing a hydraulic motor with a new operating principle. The first tests on the micromodels of the new hydraulic motors have been completed. The modelling results will be used for designing an experimental model of the small hydraulic downhole motor.

In the course of research work the three-dimensional computer modeling techniques were used in addition to the calculation methods with the manufacture of models by means of 3-D printers, as well as methods of experimental studies using bench units.

The following main results were obtained in the framework of solving the research problem:

- A new technical solution for the construction of downhole mud motor was developed and patented which allows to solve the actual problem of eliminating rotor vibration when drilling oil and gas wells employing PDC bits with a rotor speed of 240 to 450 revolutions per minute
- A new hydraulic motor model was designed and manufactured by means of a 3-D printer to study the new geometry of operating chambers, including embodiments with various forms of angular inserts
- Different hydraulic motor versions were tested at the laboratory-scale units having a transparent body, with photo and video shooting
- The operability of the new hydraulic machine was checked using liquid and gas as a working media
- The absence of rotor vibration in the hydraulic machine operating at a rotor speed of 240 to 450 rpm was experimentally confirmed
- The absence of rotor vibration in the hydraulic machine operating at a rotor speed up to 3000 rpm was experimentally confirmed (these tests were conducted to evaluate the scope of the new hydraulic machine)
- The possibility of increasing the production processability and repair of hydraulic machines was experimentally confirmed, since all operating chambers of the new hydraulic machine are formed by simple and maintainable cylindrical and flat surfaces (the design excludes technologically sophisticated screw surfaces)
- It was experimentally demonstrated that the rotor and stator of a new hydraulic machine can be manufactured without the use of elastomer
- The embodiments having with three and six angular inserts in each operating chamber were experimentally tested, these studies indicated a possible variety of options to create hydraulic machines of a new type
- The research results will be used to carry out design work, while creating an engineering prototype of a small-sized hydraulic motor designed for well-drilling

The main area of application of the hybrid hydraulic motor is horizontal drilling of oil and gas fields. Yet, some R&D findings can be used for performing other production tasks, e.g., designing the pumping facilities for oil and gas extraction and pumping.

Acknowledgment

The authors gratefully appreciate the support of the Ministry of Education and Science of the Russian Federation.

Funding Information

The work is performed as part of the applied research program funded by the Ministry of Education and Science of the Russian Federation (unique identifier: RFMEFI57715X0175).

Author's Contributions

The authors have equally contributed to the conducted research and writing of the article.

Ethics

This article is original and contains unpublished material. The authors confirm that there are no ethical issues involved.

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