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Design of a continuous wave mud pulse generator for data transmission by fluid pressure fluctuation

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ABSTRACT

High-speed downhole transmission technology is in high demand for measurement while drilling (MWD) and logging while drilling (LWD) systems which have had major roles in increasing the geo-steering and formation evaluation capacity of reach wells, difficult horizontal wells and branch wells as well as increasing drilling rates. This paper presents the conceptual design and performance of a novel continuous wave mud pulse generator with the goal of transmitting data using hydraulic pressure waves. The generator includes the rotary valve, drive shaft and bearings, rotary and static seals, motor and reducer, resolver, pressure balance structure and lower centralizer; all of these components are mounted within a rotary drill collar. In particular, the rotary valve is the key important part of the continuous wave mud pulse generator. Based on the concept of a sinusoidal signal output, an improved arc-fillet-line triangular valve orifice is designed according to the relationships between the fluid differential pressure of a thin-walled cutting edge and the fluid flow area calculated from the relative rotation angle of the rotor to the stator through the established polar coordinate equations. The highly similar sinusoidal pressure signals can be achieved by optimized valve structures, which were verified by computational fluid dynamics (CFD) simulations, where the valve flow pattern characteristics and the impact law between the gap of the stator/rotor and pressure waveform were also obtained. Moreover, the drive capability response curves of the motor driver unit with and without a load are precisely determined, and current ground hydraulic experiments indicate that the designed continuous wave mud pulse generator performs well as a whole. The generated real pressure waves exhibit clear spectrum structures with a distinctive characteristic signal.

1. Introduction

Modern measurement while drilling (MWD)/logging while drilling (LWD) operations demand a significant amount of information, which is important to the efficiency in oil and gas reservoir development [1–5], where information typically includes parameters of pressure, temperature, direction and deviation of the well bore and other logging data, such as resistivity of the various layers, sonic density, porosity, induction, self-potential and pressure gradients. The real-time transmission of these data from downhole sensors to the surface is a critical factor in safe, cost-efficient drilling wells that will enhance the oil and gas production rate. Currently, there are various existing methods of achieving this transmission, which can be divided into two categories: wired and wireless. Wired transmission technologies primarily include cables, fibers and intelligent drilling pipe transmission, whereas wireless transmission technologies include three different methods: mud pressure pulse, electromagnetic and acoustic transmission. Wired transmission permits a relatively high transmission rate but is relatively expensive to implement, and electromagnetic and acoustic transmission techniques lack reliability due to the high degree of noise generated during drilling, which makes them difficult to apply to deep and ultra-deep wells. Mud pulse transmission is advantageous due to its reliability, low development costs and ability to be applied to a wide variety of well depths; these advantages have made it the most widely used transmission method. There are three types of downhole data mud pulse transmission: negative pulse, positive pulse and continuous wave. Especially, continuous wave transmission is an extremely promising method of mud pulse transmission due to its high transmission rate and strong anti-interference abilities [6–10].

Recently, the amount of downhole data required while drilling has

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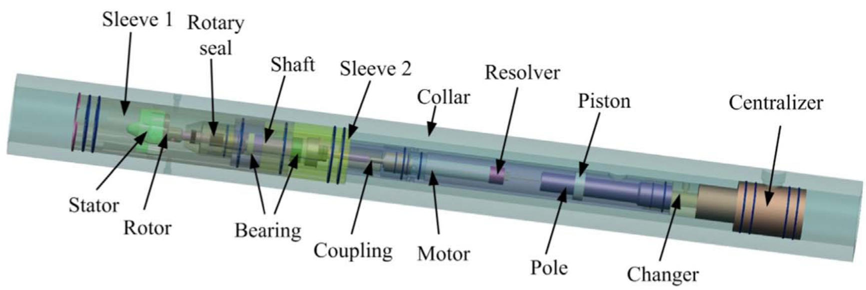

Fig. 1. 3D blueprint of a continuous wave mud pulse generator.

become more and more due to several new formation evaluation measurements as well as increasing average rate of penetration. Meanwhile, additional challenges, such as, deep & ultra-deep well exploitation, harsh mud system application, and strong variations in rigs, have emerged which propose a higher requirement for continuous wave mud pulse transmission in general and high transmission speeds in particular [11,12]. Based on the generation mechanism and propagation properties of a continuous wave mud pulse, which are heavily discussed in many studies [6,13–18], and considering the actual drilling requirement, our primary motivation in designing and building a continuous wave mud pulse generator came from the need to create a versatile, low-cost system aimed at high-speed data transmission in oil blocks during MWD and LWD applications. In this paper, a fundamental and important study on the construction of such a novel continuous wave mud pulse generator is presented, which can generate real pressure waves with a clear frequency spectrum structure of the required characteristic signals.

2. Structure design of a continuous wave mud pulse generator

Fig. 1 illustrates a 3D blueprint of a continuous wave mud pulse generator; the generator includes the valve (stator and rotor), shaft and bearing components, rotary and static seals, motor and reducer, resolver, pressure balance structure (piston/pole) and lower centralizer. All of these components are mounted in a rotary drill collar, which is also part of the generator.

Considering actual working conditions, a high-temperature, high-power brushless DC motor and reducer are preferred, and the drivetrain consisting of the shaft, bearing and coupling is designed; the mechanical rotary seal and static seal with O rings are used to ensure that the internal oil is isolated from the external mud without bidirectional leaks. The pressure balanced structure is provided to maintain the differential pressure of the internal oil and external mud pressure within an appropriate range to enhance the sealing effect. The centralizer is mounted to centralize the generator in the collar and is used as an external power supply and data communication. Two images of the continuous wave mud pulse generator are shown in Fig. 2.

3. Rotary valve design

When a continuous wave mud pulse generator works, the rotor continuously rotates along a fixed direction by a motor; the fluid between the rotor and stator is throttled with different flow areas by cross-section changes due to their relative positions, and a pressure disturbance that is transmitted in the up and down directions with sonic speed is produced, resulting in different pressure values, which increases with a decreasing flow area.

Considering the fading of the mud pressure wave signal, the spectrum of the pressure wave signals produced by the rotary valve should be concentrated within a narrow range, then the orifices of the rotary rotor and stator are typically designed with a special shape to meet the requirements of a continuous sinusoidal pressure wave output in order to increase the fundamental wave energy and suppress the harmonic energy component as the pressure transmits along the drilling pipelines [6]. Thus, the stator and rotor are the keys to a continuous wave mud pulse generator, and both always have the same number of blades and end face shape to reduce the difficulty. Because the flow path of the thin-walled edge is short and exhibits partial loss and the flow-pressure relationship is insensitive to the physical properties of the working medium, it is ideal to design the rotary valve of the continuous wave mud pulse generator. The relationship between the flow area $A(t)$ (m^2) of the valve orifice formed by the relative rotation of the rotor to the stator and the generated theoretical pressure difference $\Delta p(t)$ (Pa) is expressed in Eq. (1) [13].

$$\Delta p(t) = \frac{\rho_m Q^2}{2C_d^2 A^2(t)} \tag{1}$$

where t is the time; ρ_m is the mud density (kg/m^3), Q is the mud flow (m^3/s), and C_d is the flow coefficient.

As the literature revealed [19], the shape of the valve orifice is designed to be an arc-fillet-line triangular structure, as shown in Fig. 3. The flow area is calculated as follows.

In Fig. 3, Ψ is the valve orifice angle; β is the straight line angle of the valve orifice (slope angle); D is the rotor diameter; and O is the origin. $\theta_1(r)$ are the polar angles of any point of the corresponding lines with a certain polar distance r. Point (C) is the center of the arc with a radius of R_0, and r_0 is the distance between the origin (O) and the arc center (C); $\theta_2(r)$ is the polar angle of any point on the arc with polar distance r. Point (B) is the center of the fillet, which has a radius of R_1, and r_1 represents the distance between the origin (O) and fillet center (B). The fillet function in polar coordinates is divided into two parts, $\theta'_3(r)$ and $\theta_3(r)$ with the boundary of OB, each of which represents the polar angle of any point on the fillet with polar distance r. In particular, θ is the polar angle at the intersection of arc R_0 and fillet R_1.

In polar coordinates, $\theta_1(r)$, $\theta_2(r)$, $\theta_3(r)$ and $\theta'_3(r)$ are expressed by Eqs. (2), (3), (4) and (5), respectively.

$$\theta_1(r) = 0,\ r \in \left[\frac{D}{2}\left|(\cos\psi - \frac{\sin\psi}{\tan\beta})\right|,\ \frac{D}{2}\right] \tag{2}$$

$$\theta_2(r) = \alpha_0 - \arccos(\frac{r_0^2 + r^2 - R_0^2}{2r_0 r}),\ r \in [r_{sep},\ \frac{D}{2}] \tag{3}$$

$$\theta_3(r) = \alpha_1 - \arccos(\frac{r_1^2 + r^2 - R_1^2}{2r_1 r}),\ r \in [r_1 - R_1,\ r_{hor}],\ \ \theta_3(r) \in [0,\ \alpha_1] \tag{4}$$

and

$$\theta_3{}'(r) = \alpha_1 + \arccos(\frac{r_1^2 + r^2 - R_1^2}{2r_1 r}),\ r \in [r_1 - R_1,\ r_{sep}],\ \ \theta_4(r) \in [\alpha_1,\ \theta] \tag{5}$$

where

$$\alpha_0 = \arccos(x_0/r_0) \tag{6}$$

$$r_0 = \sqrt{x_0^2 + y_0^2} \tag{7}$$