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Mathematical model and optimum design approach of sinusoidal pressure wave generator for downhole drilling tool

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ABSTRACT

Mud pulse generators have been widely used for the real-time transmission of valuable directional and formation data from downholes with depths of thousands of meters. There have been numerous studies on the design of mud pulse generators in which the pressure waves were typically nonsinusoidal. Sinusoidal waves provide improved long-distance data transmission and signal noise suppression compared with nonsinusoidal waves. Although sinusoidal pressure wave generators have been studied in the published literature, the influence of the risks of clogging on the design of the generator for producing sinusoidal pressure waves has rarely been considered. To generate sinusoidal pressure waves and to reduce the risks of clogging, a mathematical model for the design of a sinusoidal pressure wave generator is developed in this paper. The effects of the axial and radial clearances between the rotor and stator on the design of the generator are considered in the model. An optimum design method for the generator is provided by combining the developed model and a computational fluid dynamics analysis. Finally, an experimental platform was built and experiments at frequencies 2 Hz and 10 Hz were conducted to validate the design result. The simulation and experimental results show that the optimized pressure waves closely approximate sine waves. Therefore, the developed mathematical model and optimization approach can be used to design a sinusoidal pressure wave generator.

1. Introduction

A key factor in improving the drilling efficiency is the transmission of the valuable directional and formation data from thousands of meters deep downhole to the surface during the drilling process. The methods for data transmission include mud pulse telemetry [1], acoustic wave telemetry [2], electromagnetic wave telemetry [3], and a wired drillpipe [4], among which mud pulse telemetry is still the leader due to its lower cost and because it can reach deeper wells than other technologies [5]. In recent years, new logging and measurement technologies have made it possible to collect more useful information from the downhole [6], which raises the demand for a higher data rate to transmit all of this information to the surface in real time.

Pressure wave generators are used to produce pressure waves in the drilling fluid and transmit downhole data. They can generate three types of pressure signals: negative pulse, positive pulse and continuous wave. Negative pulses are generated by momentarily reducing the pressure in the drillpipe and diverting mud from the inner drillpipe to the annulus via a valve. Positive pulses are generated in the mud column by partially blocking the flow of mud through the drillpipe via a

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Nomenclature

P_u, P_d	pressure upstream and downstream of the SPWG (Pa)
ρ	mud density (kg/m^3)
Q	discharge (m^3/s)
C_d	discharge coefficient (-)
A	flow area (m^2)
P_o, Q_o, A_o, C_{do}	upstream pressure (Pa), discharge (m^3/s), flow area (m^2) and discharge coefficient (-) while the SPWG is fully open
P_v, Q_v, A_v, C_{dv}	upstream pressure (Pa), discharge (m^3/s), flow area (m^2) and discharge coefficient (-) while the flow area $A=A_v$
ΔP, ΔP_0	calculated pressure wave (Pa), reference sine pressure wave (Pa)
t, Δt	time (s), time interval (s)
τ	relative valve opening (−)
C	mean pressure value and oscillation amplitude of the sine pressure wave (Pa)
n	wave number and the number of lobes of the orifice (-)
ω	rotor speed (rad/s)
φ	initial phase (rad)
k	relative intensity (-)
T	wave cycle (s)
α	polar angle (rad)
A_1, A_2, A_3	three regions of the flow area (m^2)
r	polar radius (m)
R, R_0	rotor radius (m), stator radius (m)
λ	coefficient for A_3 (-)
s	axial clearance and radial clearance between the stator and rotor (m)
ζ	correction coefficient (-)
L	length of the orifice curve (m)
ρ_0, ρ_{xy}	Initial correlation coefficient (-), calculated correlation coefficient (-)
v	a uniform velocity (m/s)

Notes: In the nomenclature, the symbol "-" denotes dimensionless.

valve mounted on the drillpipe. The continuous wave generator consists of a pair of rotor and stator, each of which has multiple lobes. The rotor is driven by a motor. When the rotor rotates, a continuous wave is generated in the opening or partially closed space between the lobes of the stator and rotor [7]. The operating frequencies of continuous wave telemetry can reach a frequency as high as 24 Hz, so high data transmission rates are possible [8].

Although continuous wave generators have been improved in the past ten years, their signal amplitudes are less than those generated by positive pulse systems. Until now, the types of stator-rotor orifices of the generators have mainly included rectangularly shaped, triangularly shaped, and sector lobe orifice, among others [9–12]. The pressure waves generated by these generators are not perfectly sinusoidal and consist of high-frequency harmonic components with high power factors. According to the propagation characteristic of periodic mud pressure waves in long wellbores, the amplitude of these pressure waves decreases exponentially with an increase in frequency, and the energy of the pressure signal reaching the surface is lost in the form of harmonics [13]. Based on communication theory [14], the sinusoidal carrier can effectively suppress noise from the mud channel, transmit multiple signals simultaneously on the same channel without aliasing, and spread over further distances. Therefore, to increase the data transmission rate and to enhance the strength of the signals over a longer data transmission distance, a new generator with a different stator-rotor orifice needs to be designed to generate nearly sinusoidal pressure waves, and this generator is defined as a "sinusoidal pressure wave generator (SPWG)". The sinusoidal pressure wave generated by the SPWG is also a continuous wave. Normally, the drilling fluid contains solid particles or debris. These particles should be able to pass through the peripheral orifices of the stator of the generator and then the orifices of the rotor. If the axial clearance between the stator and rotor is less than a certain value, clogging will occur, which may lead to downhole equipment failure [9]. Therefore, we need to consider the influence of the axial and radial clearances between the stator and rotor on the design of the SPWG.

Recently, there have been numerous studies on the design of SPWG. Jia [15] designed a stator or rotor with curved orifices. Theoretically, these generators can generate similar sinusoidal pressure wave signals. Zhidan et al. [16] designed an improved arc-fillet-line triangular valve orifice based on a general line triangular valve orifice. Namuq et al. [17,18] designed a continuous wave generator in which the rotor had a fan-shaped orifice and a circular hole on each lobe. He obtained good results in his test. However, all of these studies do not consider the effects of the axial and radial clearances. The flow through the clearances and orifices of the pressure wave generator is three dimensional. It is difficult to directly calculate the flow areas using a mathematical model. For these fluid structures in a three-dimensional flow field, many researchers