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An experimental rig for near-bit force measurement and drillstring acoustic transmission of BHA

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ABSTRACT

An experimental rig for near-bit force measurement and drillstring acoustic transmission of bottom-hole assembly (BHA) is designed and implemented to investigate downhole dynamic behaviors of BHA. By using a developed dynamic force sensor device with a four-straight beam strain gauge, the rig can measure axial, lateral forces and torques exerted on simulated drillstring while rotating. For the upward transmission of downhole dynamic force data, drillstring acoustic telemetry method is further analyzed by transient numerical simulation. Considering acoustic signal attenuation and transmissibility, a narrow pulse on–off keyed modulated time-delay signal transmission method is developed. The near-bit force measurement experiments of BHA are performed under different weight on bit loads, deviation angles and drill pipe combinations. The obtained force data are transmitted via acoustic waves propagating along the simulated drillstring. The results show that acoustic transmission rate is approximated 77 bit/s along 6.4-m simulated drillstring under 1-W power excitation in the laboratory.

1. Introduction

In the oil industry, measurement-while-drilling (MWD) surveying is one of the important prerequisites for the successful completion of the drilling process [1]. Drillstrings, especially the bottom-hole assemblies (BHAs), are subjected to severe axial, transverse and torsional vibrations in MWD. In recent years, drillstring dynamics has been proved to be particularly critical in directional drilling where the control of hole deviation is essential [2,3]. Without an accurate assessment of the forces and stresses all along the drillstring, the operator may risk serious well damage. Over the last twenty years, theoretical models of hole trajectory control and BHA in the borehole have been studied. Menand et al. focused their attention on a new numerical method to address the 3D static mechanical behavior of a complete drillstring moving and freely rotating inside a wellbore [4]. Considering the bit/formation and drillstring/borehole wall interactions as well as other geometric and dynamic nonlinearities, Christoforou and Yigit proposed a fully coupled model for axial, lateral and torsional vibrations of actively controlled drillstring [5]. The theoretical simulations with the proposed models provide deeper insights into the dynamic behaviors of BHA. However, the accuracy of their theoretical modeling is often limited due to the simplified assumptions and the uncertainties in the boundary conditions.

With the development of electronic circuits and digital signal processing technologies, some downhole measurement tools are developed to collect downhole sensing data while drilling, such as weight on bit (WOB), torque, dynamic force, and bearing condition [6]. Once these data are transmitted to the surface, they can be used for understanding the drillstring dynamics, improving the theoretical models for BHA and then optimizing the drilling in a real time way [7]. The various downhole telemetry methods that have been attempted include mud pulse telemetry, high-speed drillstring telemetry, wireline telemetry, extremely low frequency electromagnetic (EM)

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telemetry and drillstring acoustic telemetry. The mud pulse telemetry is the most commercially successful method. However, the data transmission rate is limited to a few bits per second due to attenuations and spreading of pulses. When highly compressible underbalanced drilling fluid is used, such an approach may become ineffective [8]. High-speed drillstring telemetry can be implemented by using a unique system of wired drill pipes and associated drilling tools connecting the MWD string to the surface [9]. Because special drill pipes and special tool joint connectors are required, the cost of the drilling operation will be substantially increased. For wireline telemetry, it is prone to failures caused by the abrasive conditions of the mud and the wear abrasions caused by the rotation of the drill string [10]. In addition, EM telemetry has been considered for MWD services, but EM signals also encounter high attenuation in regions of low formation resistivity, in cased holes and where borehole fluid is highly conductive [11]. The data transmission along the drillstring via acoustic stress waves offers another communication possibility. As early as 1948, acoustic telemetry was identified as a potential method for high speed communication. Since the drillstring is a periodic structure of pipe and threaded tool joints, the transmission characteristics exhibit a banded and dispersive structure [12]. Compared with the other transmission methods, drillstring acoustic telemetry has the advantages of potentially high data rate and being relatively unaffected by the formation. Furthermore, it is presently an effective way to transmit 10 bits/s over a range of 1 km [13]. Consequently, drillstring telemetry method for sensing data transmission is chosen in this paper.

The phenomena of drillstring vibrations and their effects on drilling performance have been the subject of analytical and field investigation. For the dynamic behaviors caused by downhole forces near the drill bit cannot be obtained directly by the accelerometers, one such technique is to use strain gauges. Those commercially available strain gauges can only measure very limited feature parameters separately, such as axial forces, shear forces or torques. Several strain gauges are required when multiple parameters are detected at the same time, which leads to the inconvenient assembly and wire connection of separate strain gauges. Techniques have been developed for measuring the WOB and torque-on-bit, as well as shear forces and bending moments working on the bit [14,15], where an apparatus for measuring force is designed based on the particular configuration of different strain gauges on the drillstring. The patented apparatus is adapted for downhole force measurement. The techniques fail to describe wireless telemetry methods of downhole force data. Retrieving and replacing damaged downhole tools is also an extraordinarily expensive and time-intensive process. The existing MWD testing facilities lack necessary near-bit dynamic force attributes in real time to characterize the interrelation between bit trajectory control and BHA. Particularly in China, because of the high downhole testing costs and shortage of high-powered downhole measurement tools, more attentions are focused on such theoretical research works rather than experimental and downhole measurement. Therefore, experimental studies of drillstring dynamics are currently essential to complement the theoretical studies and to alleviate the complexity of dynamic models [16]. Raymond et al. are developing an advanced laboratory simulation device to allow the dynamic properties of BHA to be reproduced in the laboratory [17]. But their work is mainly limited to the axial mode of the drillstring. In this paper, an experimental rig integrating dynamic force sensor device and acoustic transmission device is designed and implemented. Considering only limited parameter measurement of existing commercial force sensors and experimental analysis of BHA behaviors, the dynamic force sensor device is designed particularly to detect simultaneously the multiple near-bit parameters, including axial force, radial force and torque, imposing on the simulated drillstring. The acoustic transmission device is adapted to transmit the obtained force data via acoustic waves along the simulated drillstring. Then the received data after acoustic transmission are retrieved to investigate downhole dynamic behaviors of BHA in the laboratory.

2. Method setup

The schematic view of the rig is shown in Fig. 1. It mainly consists of a dynamic force sensor device, an acoustic transmission device and a finite-length simulated drillstring. According to the analogical principle, a set of drill pipes is adopted to construct the simulated drillstring. The drill pipes made of 45# carbon steel are screwed end-to-end to simulate practical drillstring combinations. The simulated drillstring is driven by a hydraulic pressure drive device to rotate at a certain rotation speed. The dynamic force sensor device is located at adjacently to the near-bit part of the simulated drillstring. It measures the dynamic forces imposing on the simulated drillstring during rotation. The force data are recorded in the flash memory. Then, the acoustic transmission device is used to read these data from the memory while the rotation of the simulated drillstring stops. The original force data are transmitted via acoustic wave propagation along the simulated drillstring. At the receiver end, the received acoustic data are processed and then sent to the computer, where the near-bit force parameters are calculated based on the proposed dynamic force measuring principle.

2.1. Dynamic force measurement of BHA

The dynamic force sensor device shown in Fig. 1 is formed by a four-straight beam strain gauge sensor as shown in Fig. 2. Such a configuration is consistent with the practical application, where downhole sensors are positioned in a cylindrical drill collar locating adjacent to the bit. One end of the sensor is connected with the end of the simulated drillstring and the other end is clamped by a three-jaw chuck. Using the strain gauges as the sensing elements, the sensor device can dynamically measure the axial force F_z, the torque M, the radial forces F_{rx} and F_{ry} exerted on the rotating simulated drillstring.

The axial force measurement principle accords with the conventional column sensor. The strain gauges R_1, R_2, R_3, and R_4 in Fig. 2 are attached to the outer surface of rectan-