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Development and testing of kick detection system at mud line in deepwater drilling

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ABSTRACT

Well control issues have posed significant challenges to deep water drilling construction. The success of early kick detection is an essential part of safe well control operations. Due to the characteristics of unresponsive prediction and low precision, conventional kick detection methods cannot meet the demands of deep water well control. This article proposed a more advanced kick monitoring method, which functions by adopting an ultrasonic device to monitor the annular flow velocity. Based on the Doppler principle, an early kick detection (EKD) prototype was successfully developed, which enables the annular flow velocity of the drilling fluid to be measured. Bearing-pressure experiments of 15 MPa were performed to verify the reliability of the ultrasonic sensor under mud line. The results of lab testing demonstrate that the EKD prototype can be used to measure stable annular flow velocities when the gas injection rate is less than 10%. The EKD prototype presented in this paper is valuable for timely kick detection in deep water drilling.

1. Introduction

Early kick detection for deep water drilling is an important means for ensuring the safety of well control. The gases entering into the annular are not free gas in form, but dissolved gas exists (Hargreaves et al., 2001; Santos et al., 2003a, 2003b; Avelar et al., 2009). Drilling fluid returns to the well head from the down hole; the dissolved gas gradually precipitates and gas undergoes continuous expansion because of the pressure loss and temperature variation. The closer the well heads are, the greater the drilling fluid flow rate and the higher the difficulty in controlling the wellbore pressure will be (Cornish, 1976; Colt, 1984; Jardine et al., 1991; Alhuthali et al., 2010). Therefore, the sooner the kick is found, the less formation fluid enters into the well bore. This causes the casing pressure to decrease and kills the maximum casing pressure; it is more beneficial for the safety of shut-in and well killing operation. Consequently, early kick detection is crucial for deep water well control.

Present kick detection methods can be divided into three categories follows (Speers and Gehrig, 1987): (1) Measuring the flow difference between the inlet and outlet: determines whether kick occurred by measuring the flow difference and pit the gain (Orban and Zanker, 1988; Henry et al., 2006). Both Weatherford and Schlumberger have developed a similar kick detection system which considered the impact of ship's heaving on outlet flow (Orban et al., 1987; Orban and Zanker, 1988). Furthermore, Schlumberger applied the Bayes method to calculate the probability of kicks (Hargreaves et al., 2001). (2) Monitoring free gas in the annulus: determines whether kick occurred by measuring the acoustic wave velocity that is significantly influenced by the free gas (Stokka et al., 1993a, 1993b; Bang et al., 1995a, 1995b; Dashti and Riazi, 2014). Based on this method, European Elf and Statoil used an ultrasound of the wellhead to monitor the free gas in the annulus (Stokka et al., 1993a, 1993b; Bang et al., 1995a, 1995b). (3) The parameters from logging or measurements in the bottom of the well are used (Ward and Andreassen, 1998; Bryant et al., 2004): Micro-flux drilling technology developed by Weatherford measures the micro-flux changes and the combined plane wave decomposition, the equivalent circulating density (ECD), the real time measurements in the bottom and the pressure control system to monitor the micro-flux changes, which realized the purpose of safely controlling the bottom hole pressure. Baker Hughes developed the PressTEQ tool. This tool, similar to Micro-flux drilling, measures the real time bottom hole pressure and the ECD while instantaneously monitoring the flux changes (Santos et al., 2003a, 2003b). Concurrently, Baker Hughes developed another down hole kick detection tool. This tool used a gauging nipple, implemented

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on the bottom hole assembly, to monitor the free gas by measuring acoustical impedance changes of the drilling fluid in the annulus (Chemali et al., 2007). Additionally, Atbalance married together the flow difference method, the liquid level method, the logging-while-drilling and the annular pressure-while-drilling to develop a dynamic annular pressure control drilling system for early kick detection (Roes et al., 2006).

However, the above-mentioned kick detection methods have some limitations, such as unresponsive prediction, low precision, etc. Therefore, these methods are not sufficient to meet the deep water well control demands. If kick can be detected early at the mud line, a longer warning time will be available for well control, which has an important practical significance in deep water well control. The security of the riser itself is of the utmost importance for deep water drilling, and the mechanical integrity of the riser should not be destroyed. A separate gauging nipple should not be installed between the riser and wellhead. Accordingly, only non-intrusive measurement apparatus can be used to monitor kick at the mud line, ultrasonic measurement is only the primary non-invasive measurement approach. Based on Doppler's principle, this paper establishes a theoretical model of the annular return velocity using the ultrasonic Doppler method, and then the Doppler ultrasonic flow measuring system was developed. The influences of density and injected gas rate on the annular return velocity were tested under mono- and three-channel conditions.

2. Flow velocity measurement using the ultrasonic Doppler method

2.1. Principle of velocity measurement using the Doppler method

When the direction of wave propagation, the wave source and the receiver velocity are not collinear, the frequency of the wave source can be expressed by Eq. (1).

$$f' = f\frac{c \pm u_2 \cos\theta_2}{c \pm u_1 \cos\theta_1} \tag{1}$$

where f' is the frequency of the wave source, f is the frequency received by the receiver, c is the velocity of the wave propagating in the medium, u_1 and u_2 are the velocities of the wave source and the receiver, respectively, and θ_1 and θ_2 are the angle between u_1 and the line passing through the wave source and the receiver and the angle between u_2 and the line, respectively.

As shown in Fig. 1, the angle between the ultrasonic beam and the velocity of the fluid is α, the ultrasonic propagates in the fluid at a velocity c, and the fluid and the suspended particles occur in the fluid flow at the same velocity u.

When the ultrasonic beam encounters a solid particle on the axis of the pipeline, the particle moves along the axis at a velocity u. For the ultrasonic transmitter, the particle closes at a velocity $u\cos\alpha$, so the frequency of the ultrasonic beam received by the particle (f_2) should be higher than the frequency of the transmitted ultrasonic beam (f_1). This case can be considered as a sound source standing still while an "observer" is moving. The solid particle scatters ultrasonic beams to the receiver, because it closes the receiver at a velocity $u\cos\alpha$, therefore, the frequency of the ultrasonic beam received by the receiver (f_3) increases again. This case can be considered as a sound source moving while an "observer" is standing still. Similarly, the frequency of the ultrasonic beam received can be calculated using Eq. (2):

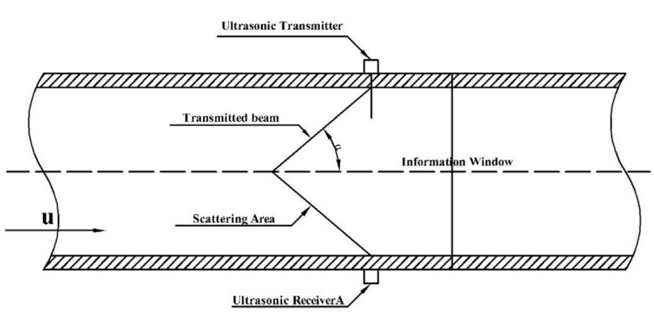

Fig. 1. Schematic diagram of the Doppler measurement.

$$f_3 = f_1\frac{c + u\cos\alpha}{c - u\cos\alpha} \tag{2}$$

The difference between the frequency of the ultrasonic beam received by the receiver and the frequency of the transmitted ultrasonic is known as the Doppler frequency shift (f_d), which can be obtained from the following equation:

$$f_d = f_3 - f_1 = f_1\frac{2u\cos\alpha}{c + u\cos\alpha} \tag{3}$$

The fluid velocity is far less than the ultrasonic velocity and can be neglected. Eq. (3) can then be expressed as:

$$f_d = f_3 - f_1 \approx f_1\frac{2u\cos\alpha}{c} \tag{4}$$

The fluid velocity can be written in the following forms:

$$u = \frac{c}{2f_1\cos\alpha}f_d \tag{5}$$

The volume flow can be calculated as:

$$Q = \frac{Ac}{2f_1\cos\alpha}f_d \tag{6}$$

where f_1 and f_3 are the frequency of the transmitted signal and the frequency of the received signal, respectively, f_d is the Doppler frequency shift, α is the angle between the ultrasonic beam and the velocity of the fluid, u is the fluid velocity, c is the velocity of the ultrasonic beam propagating in the fluid, A is the flow area of the measured pipeline and Q is the fluid flow.

Eq. (6) illustrates that the fluid volume flow is heavily dependent on the Doppler frequency shift. Therefore, accurate calculation of the Doppler frequency shift is of vital importance for determining the fluid volume flow for early kick detection.

2.2. Improvement of the measurement algorithm

It can be seen from Eq. (5) that the fluid velocity obtained is relevant to the velocity of the ultrasonic beam in the fluid (c). The velocity (c) is further associated with the fluid temperature. Therefore, it is difficult to ensure that the ultrasonic velocity is constant. To eliminate this impact, an acoustic wedge structure can be provided outside the pipeline so that ultrasonic beam must pass through the acoustic wedge and pipeline wall to enter the fluid. As shown in Fig. 2, assuming that the ultrasonic velocity in the acoustic wedge is c_1, the ultrasonic velocity in the pipe wall is c_0, the ultrasonic incident angle is φ_0, φ_1 and φ are refraction angle, respectively, and the angle between the ultrasonic and the velocity (u) is α. Based on the refraction principle, the following equation can be obtained:

$$\frac{c_1}{\sin\varphi_0} = \frac{c_0}{\sin\varphi_1} = \frac{c}{\sin\varphi} \tag{7}$$

Eq. (7) can be transformed to Eq. (8) using $\sin\varphi = \cos\alpha$:

$$\frac{c}{\cos\alpha} = \frac{c_1}{\sin\varphi_0} = \frac{c_0}{sin\varphi_1} = \frac{c}{\sin\varphi} \tag{8}$$

Substituting Eq. (8) into Eq. (5), the fluid velocity can be