In-service Detection of Longitudinal Cracks on Drill Pipe using Induced Circumferential Current

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Abstract. Drill pipes are critical facilities in oil & gas industry suffering from alternating stress and corrosion environment. So stress corrosion cracking (SCC) is one of the most common defects on drill pipes. The SCC usually begins axially and develops into longitudinal crack leading to the failure of drill pipes in the end, which causes massive property damage and casualty. In this paper, an in-service detection method is presented for longitudinal cracks detection on drill pipe using circumferential current induced by a coaxial excitation coil fixed on wellhead. The finite element method is proposed for analyzing the characteristic signals of longitudinal cracks. The in-service detection system is set up and the longitudinal crack test experiment is carried out. The results show that the longitudinal cracks can be quantitatively detected using the induced circumferential current during the tripping operation. The induced circumferential current can be used for in-service detection of longitudinal cracks on drill pipe.

1. Introduction

Drill pipes are critical facilities for drilling operation in oil & gas industry, which suffer from alternating stress and corrosion environment. Due to the stress and corrosion, stress corrosion cracking (SCC) is easily introduced on the drill pipes. Typically, the SCC forms in colony containing numerous short, narrow, shallow, axially-oriented cracks [1-2]. As the service time of drill pipes increases, the SCC gathers and extends into longitudinal cracks leading to the failure of drill pipes in the end, which causes massive property damage and casualty. About 1000 drilling accidents happen in China annually and 50% - 60% are related to the failure of drilling pipes, which costs over 50 000 000 yuan every year [3]. So it is really necessary to detect the drill pipes efficiently and timely.

Magnetic flux leakage (MFL) is a conventional non-destructive testing (NDT) method for ferromagnetic materials. However, it is not sensitive to narrow longitudinal cracks due to the lack of leaking fluxes [4]. Because of the paraffin deposit on the surface of drill pipes, the magnetic particle inspection (MPI) is inadequate to detect cracks on drill pipes [5]. Eddy current testing (ECT) is sensitive to lift-off and could not make rapid quantitative assessment
of the narrow cracks [6]. It is hard for ultrasonic testing (UT) to test shallow cracks on the surface of drill pipes [7].

In our previous work [8-10], we find the coaxial encircling coils can induce a broad uniform circumferential current field on the surface of pipe string, as shown in Fig. 1(a). The current field will be disturbed when the cracks is present on the surface of pipe string. As shown in Fig. 1(b), the induced current field bypasses the crack making the magnetic field distorted. By measuring the distorted magnetic field, the cracks can be detected quantitatively [11-12].

Fig. 1. The circumferential current field on the surface of pipe string is induced by coaxial encircling coils. (a) The coaxial encircling coils. (b) The induced broad uniform circumferential current field.

This paper aims to detect longitudinal cracks on drill pipe in service using the circumferential current induced by coaxial encircling coils. The coaxial encircling coils are fixed on the wellhead. Thus, the cracks can be detected in service when drill pipe is lowered into or raised from the wellhead (tripping operation). The finite element method (FEM) is proposed to extract the characteristics signals of longitudinal cracks on the surface of drill pipes. The relationship between the characteristics signals and the size of cracks is analyzed. To avoid shaking effect caused by drill pipes, the lift-off effects of coaxial encircling coils is simulated by FEM model. The in-service drill pipe cracks detection system is set up and the test experiment is carried out to test the crack on drill pipe.
2. Simulation

2.1 Model setup

According to API standard, the common 2.875 inch S315 small-caliber drill pipe is selected as the FEM model. The FEM model is set up using ANSYS software, as shown in Fig. 2(a). The axial direction of the drill pipe is set as X-axis while the radial direction is set as Z-axis. The model consists of a mild steel drill pipe and coaxial encircling excitation coils. Because of the symmetry, half of the FEM model is built to reduce the amount of calculation in ANSYS. The dimensions of the model are shown in Table 1. The longitudinal crack is a rectangular surface cracking, which lies in the middle of the drill pipe. The characteristic parameters are shown in Table 2. The excitation coils are loaded with a sinusoidal signal whose amplitude is 1V and frequency is 6K Hz [13-14].

Fig. 2(b) shows the current density on the surface of drill pipe. It is clear that there is a broad nearly uniform circumferential flowing current which bypasses the longitudinal crack. The current field turns around at the tips of longitudinal crack. The current density decreases in the center of longitudinal crack for the material discontinuity [15].

Fig. 2. The FEM model of circumferential current induced by coaxial encircling coils. (a) The FEM model. (b) The induced circumferential current field on the surface of drill pipe.
Table 1. The dimensions of FEM model

<table>
<thead>
<tr>
<th>Model</th>
<th>Diameter /mm</th>
<th>Length /mm</th>
<th>Width /mm</th>
<th>Depth /mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>String (D/d)</td>
<td>73/32</td>
<td>120</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Excitation coil</td>
<td>93</td>
<td>40</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Longitudinal crack</td>
<td>—</td>
<td>20</td>
<td>0.8</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 2. The characteristic parameters of FEM model

<table>
<thead>
<tr>
<th>CoiIdiameter</th>
<th>Turns of coil</th>
<th>String material</th>
<th>Voltage</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.15mm</td>
<td>350</td>
<td>Mild steel</td>
<td>1v</td>
<td>6KHZ</td>
</tr>
</tbody>
</table>

2.2 Characteristic signals

To get the characteristic signals of the longitudinal crack, a path is defined in X direction above the crack at the lift-off of 2 mm. The magnetic field in X direction (Bx) and Z direction (Bz) are extracted on the defined path. As shown in Fig. 3, Bx shows a trough in the center of the longitudinal crack while Bz shows a negative and positive peak at the end of the longitudinal crack.

Fig. 3. The magnetic field (Bx and Bz) on the defined path with a lift-off of 2 mm above the crack.
In order to find the relationship between characteristic signals and the size of cracks, the characteristic signals of different size longitudinal cracks are analyzed. As shown in Fig. 4(a), the trough of $B_x$ increases as the crack depth grows up. This is due to the increase of crack depth and the current density turns smaller. So the trough of $B_x$ becomes deeper. Meanwhile, due to the gathered current density around the tips of cracks, the distance between the negative and positive peaks of $B_z$ increases as the crack length increases, as shown in Fig. 4(b). The results indicate that the $B_x$ is the characteristic signal of crack depth, which contains the depth of longitudinal cracks on drill pipe. The $B_z$ is the characteristic signal of crack length and the distance between the negative and positive peaks of $B_z$ reflects the length of longitudinal cracks on drill pipe. So we can make quantitative detection of longitudinal cracks on drill pipe using the circumferential current induced by coaxial encircling coils.

2.3 The lift-off effect

During the tripping operation, the shaking of drill pipe is inevitable. Thus, it is necessary to analyze the lift-off effect of the coaxial encircling coils. The lift-off is the distance between the drill pipe and coaxial encircling coils. The $B_x$ and $B_z$ is extracted above the crack with a series lift-off (10mm, 15mm, 20mm, 25mm, 30mm, 35mm, 40mm, 45mm, 50mm). The detection sensitivity, $S_x$ and $S_z$, are given as follows to reduce detection error and improve the signal to noise ratio [16-17].

$$S_x = \frac{\Delta B_{x_{\text{max}}}}{B_{x_0}} \times 100\%$$

$$S_z = \Delta B_{z_{\text{max}}}$$

Where $B_{x_0}$ is the amplitude of $B_x$ signal without crack, and $\Delta B_{x_{\text{max}}}$ and $\Delta B_{z_{\text{max}}}$ are the maximum perturbations of $B_x$ and $B_z$ caused by crack respectively.

Table 3 shows the detection sensitivity $S_x$ and $S_z$ with a series lift-off (10mm, 15mm, 20mm, 25mm, 30mm, 35mm, 40mm, 45mm, 50mm). The detection sensitivity $S_x$ almost keeps the same, while as shown in Fig. 5, $S_z$ decreases as the lift-off increases. However, when the lift-off is among 10-40 mm, the $S_z$ is always larger than 0.01 Tesla. The results show that the detection sensitivity of $B_x$ is basically impregnable within an appropriate lift-off range and the detection sensitivity of $B_z$ is acceptable when the lift-off is among 10-40 mm. So the tolerance of lift-off can provide a buffer distance for the drill pipe and coaxial encircling coils to soften the shaking effect of drill pipe.
Fig. 5. The detection sensitivity $S_z$ against the lift off.

Table 3. The detection sensitivity $S_x$ and $S_z$

<table>
<thead>
<tr>
<th>lift-off height/mm</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>15</th>
<th>30</th>
<th>35</th>
<th>40</th>
<th>45</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_z /\times 10^{-2}T$</td>
<td>2.421</td>
<td>2.123</td>
<td>1.792</td>
<td>1.569</td>
<td>1.349</td>
<td>1.196</td>
<td>1.047</td>
<td>0.940</td>
<td>0.836</td>
</tr>
</tbody>
</table>

Fig. 6. The experimental system. (a)The system chart. (b) The coaxial encircling coils and detecting sensor array.
3. Experimental test and analysis

3.1 Experimental system

The induced circumferential current experimental system is set up, as seen in Fig. 6. The coaxial encircling coils are wound on the non-ferromagnetic yoke, which is fixed on the wellhead by flexible material. The 18 detecting sensors are installed inside the non-ferromagnetic yoke with equal spaced. So all cracks can be detected on the whole surface of drill pipe with one pass scanning. Three ball transfers are installed on the yoke to keep probe coaxiality and lift-off stability (10 mm for the excitation coil and 2 mm for detecting sensors). The signal processing and defect identification system are set in driller house.

The signal generator produces an alternating sine waveform signal (frequency 6 KHz and magnitude 1 V). Through power amplifier, the signal is transferred into the coaxial encircling coils. The coaxial encircling induces a broad uniform circumferential current field on the surface of drill pipe. The detecting sensors will pick up the distorted magnetic field caused by the longitudinal crack. The detecting signal is filtered, amplified and then digitized by A/D acquisition card. The signal is sent to the computer for crack identification by intelligent software.

3.2 Cracks detection experiment and analysis

The specimen is a mild steel pipe which is cut out from the drill pipe (2.875 inch). The crack is a rectangular longitudinal crack which is the same as the FEM model. The drill pipe is pulled out from the non-ferromagnetic yoke. The detecting sensor array picks up the distorted magnetic field and the computer shows the characteristic signals. The butterfly plot is employed to identify the cracks, in which Bx is plotted against Bz. A distinctive butterfly-shaped loop is drawn on the screen to decide whether a crack is present or not.

The test results are showed in Fig. 7. It is clear that the characteristic signals from channel 5 and 7 are chaotic, which cannot be used for recognizing the crack. The characteristic signals in channel 6 are obvious. There is a deep trough in Bx while there is a positive and negative peak in Bz. The butterfly plot shows the present of the cracks. It suggests that the crack is around the sensor of channel 6. The size information of the crack can also be calculated from the characteristic signals Bx and Bz as well. It can be summarized that the longitudinal crack on drill pipe can be detected effectively using the circumferential current experimental system.
Fig. 7. The test results. (a) The signal from channel 5. (b) The signal from channel 6. (c) The signal from channel 7.

4. Conclusion

In this paper, the circumferential current induced by coaxial encircling coils is present for in-service detection of longitudinal cracks on drill pipe. The FEM model is employed to obtain the characteristic signals of longitudinal cracks on drill pipe. The relationship between the characteristic signals and the cracks size is analyzed by FEM model. Meanwhile, the lift-off effect of the coaxial encircling coils is simulated to soften the shaking effect of drill pipe. Finally, the in-service drill pipe cracks detection system is set up and the longitudinal crack is detected on drill pipe with sensor array. The results from simulation and experiment show that the characteristic signals contain the size information of longitudinal crack on drill pipes. The longitudinal crack can be detected effectively in service on drill pipe using the circumferential current experimental system.

This work is supported by the National Natural Science Foundation of China (No. 51574276), the Shandong Provincial Natural Science Foundation, China (No. ZR2015EM009), the Fundamental Research Funds for the Central Universities (No.15CX05024A), the Applied Basic Research Program of Qingdao City, China (14-2-4-49-jch), the China Postdoctoral Science Foundation (No. 2013M540568 and No.2014T0666), the Postgraduate Innovation Project of China University of Petroleum (No. YCX2015039 and YCX2014040).

References